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ABSTRACT

The environmental control system is an essential subsystem of an aircraft, which has to achieve some vital tasks. These include the setting of the desired temperature, humidity and cabin pressure, as well as ensuring the fresh air or oxygen supply and air quality. The requirements must be achieved at very different ambient conditions. This refers to the environmental conditions in the flight and ground cases, and also to the different climatic zones. In addition, the existing interfaces to the aircraft must be taken into consideration.
State of the art in currently used commercial aircrafts is an environmental control system, which is based on the air cycle and is driven by bleed air from the engine. This technology allows only a significantly lower coefficient of performance for the given boundary conditions compared to a vapor-compression refrigeration system. Therefore the potential application of the vapor cycle in the aircraft air conditioning system is investigated in a research project with the cooperation partner Airbus. The new system has to be developed as a replacement of the existing air cycle system (retrofit).
In a detailed simulation model the thermodynamic state variables are calculated for every element and different operating cases. The calculation results are then used to investigate and size the main components, e.g. heat exchangers and turbo-machines. After the optimization of the system parameters and the individual components the new system is compared with the existing system. The benchmark shows a considerable decrease of about 26% bleed air mass flow for the reference case on the ground and 28% for the operating case in flight, both at hot ambient conditions.

1. INTRODUCTION

The currently used environmental control system is based on an open, 2-stage air cycle. The system is driven by the jet engine via high pressure bleed air, which is expanded to cabin pressure in the turbine. The bleed air is also used as fresh air, respectively oxygen supply for the passengers. The scheme of the air cycle machine in current aircrafts is shown in Figure 1.

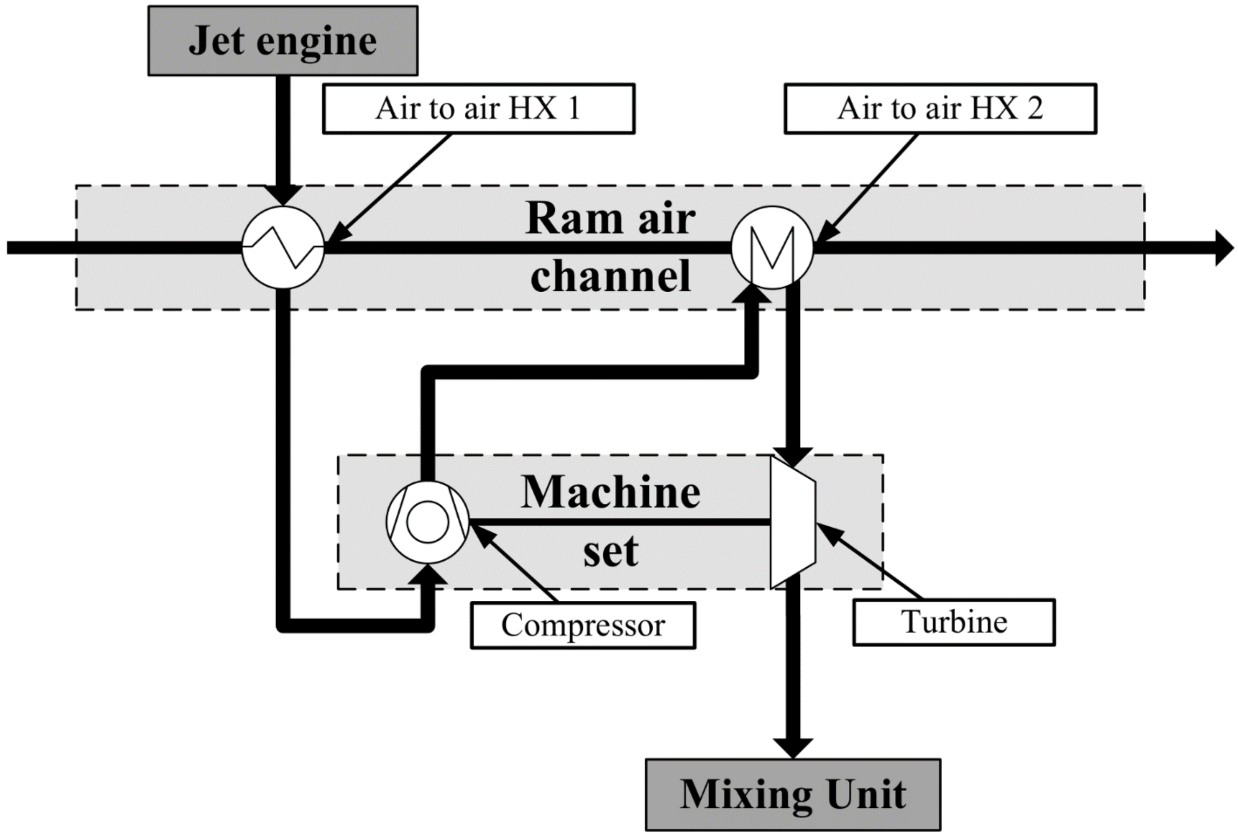


Figure 1: Scheme of the pneumatically driven air cycle machine for the air-conditioning of aircrafts, according to Airbus (2012)

At first the bleed air flow from the jet engine is cooled almost isobaric in the first air to air heat exchanger and is then compressed polytropic in the air compressor. Afterwards the bleed air is cooled isobaric in the second air to air heat exchanger and is finally expanded polytropic to cabin pressure in the air turbine. Because of the weight requirements in the aviation industry the machine set consists of two turbo-machines, which are connected by a shaft. The air to air heat exchangers are installed in the ram air channel. This channel is situated in the central bottom part of the airplane and has a ram air inlet on the outside surface. The ram air flow is needed to dissipate the heat from the bleed air to the ambience. After the air-conditioning pack the bleed air is led in the mixing unit, mixed with recirculated air from the cabin and injected back to the cabin. The air cycle machine is the reference system in this study for the benchmark with the newly developed vapor cycle machine.

The air cycle has a lower coefficient of performance than the vapor-compression cycle at comparable temperature level. This is because in the air cycle machine it is not possible to reach an isothermal state change with a finite number of compressors and heat exchangers. But in a vapor-compression cycle an isothermal state change is possible because the isobars and isotherms coincide in the two phase region of the refrigerant. The ideal coefficient of performance is given by the Carnot cycle, which consists of two isentropic and two isothermal state changes.

Therefore the application of the vapor-compression cycle as replacement for the first stage of the air cycle offers a considerable savings potential and is the central idea of the present feasibility study. The requirements, that the new air-conditioning pack can be installed in currently used aircrafts (retrofit) and no interfaces to other subsystems have to be changed, turn out as key design criterion.

To illustrate the fundamental processes in the old and new environmental control system, the state changes of the bleed air for various system concepts are shown in Figure 2 in an h-s-diagram.

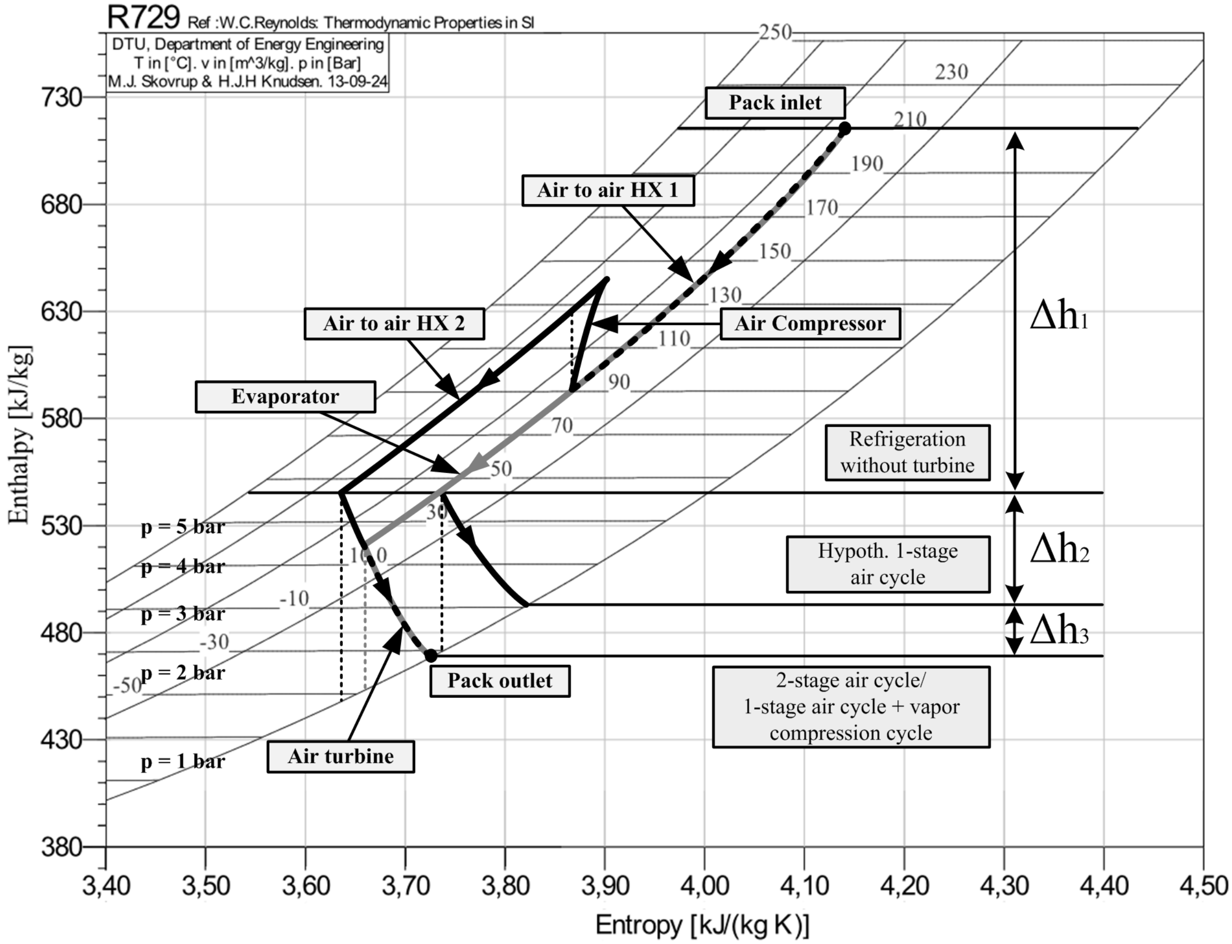


Figure 2: Qualitative comparison of the basic system concepts for the air-conditioning of aircrafts in the h-s-diagram (Skovrup and Knudsen, 2013) of bleed air

The bleed air is taken from the jet engine under increased pressure and temperature compared to the cabin conditions. The first part of the enthalpy difference Δh_1 is achieved by cooling with ambient air via an air to air heat exchanger. The reference case is the "hot day on ground". The second enthalpy difference Δh_2 is generated by the expansion of the fluid in the turbine. Together with the jet engine this process can be described as an open, 1-stage air cycle. However, the outlet temperature is not sufficient in order to create the desired cabin environment under all operating conditions. In the air cycle machine the desired cabin entry states are realized by an additional second stage, which is based on an air cycle as well. The associated air compressor and the second air-to-air heat exchanger are indicated in the diagram to the corresponding state changes according to the system in Figure 1. The resulting enthalpy difference Δh_3 is sufficient to achieve the desired cabin conditions. Now the idea is to replace the inefficient second stage of the air cycle by a vapor-compression cycle. The corresponding state change (evaporator) is shown in grey in Figure 2 and is implemented by a separate refrigerant circuit. The new air-conditioning pack will be a hybrid system, consisting of a 1-stage air cycle and a 1-stage vapor-compression cycle.

2. REQUIREMENTS AND BOUNDARY CONDITIONS

The main tasks of the environmental control system are the adjustment of the cabin conditions:

- Temperature (about 21 to 27 °C)
- Pressure (about 0,75 in flight to 1,013 bar on ground)
- Humidity (max. 60%, no water separation in flight)
- Fresh air/ oxygen supply (min. 0,28 [m^3/min·Pax] or min. 0,18 [m^3/min·Pax] in failure cases)

The airworthiness standards of Europe (Joint Aviation Authorities, 2013) and the USA (Federal Aviation Administration, 2013), as well as internal specifications of Airbus form the basis of these requirements. To determine the cabin input states a comprehensive simulation model of the cabin is necessary. This model is not part of the feasibility study. These values were determined by Airbus and are regarded as boundary conditions for the output states of the air-conditioning packs. Furthermore, the input states of the air-conditioning packs for the bleed air are specified by Airbus.

Further boundary values are determined by the ambient conditions. The air-conditioning system must cover the whole range of different altitudes and various climatic zones. The International Standard Atmosphere (ISA) defines a linear temperature profile from the ground up to an altitude of 11000 m (15°C initial temperature and -0.0065 K/m temperature gradient over the altitude). In addition to the standard conditions, the characteristics for a hot (+23°C initial temperature) and a cold case (-38°C initial temperature and reduced temperature gradient over the altitude of -0.0026 K/m starting at about 4200 m) is defined. The humidity is 80% over the whole altitude range up to a maximum water load of 19 g/kg. The corresponding graphs for the temperature, pressure and water load over the altitude are shown in Figure 3. The highlighted area represents the complete operating map, which must be covered by the new system.

For the simulation of the new vapor cycle machine five operating cases are defined, which represent the extreme cold and hot conditions on the ground and in flight, as well as the ISA case in flight. The exact environmental conditions from internal data can vary slightly from the International Standard Atmosphere and are based on many years of experience.

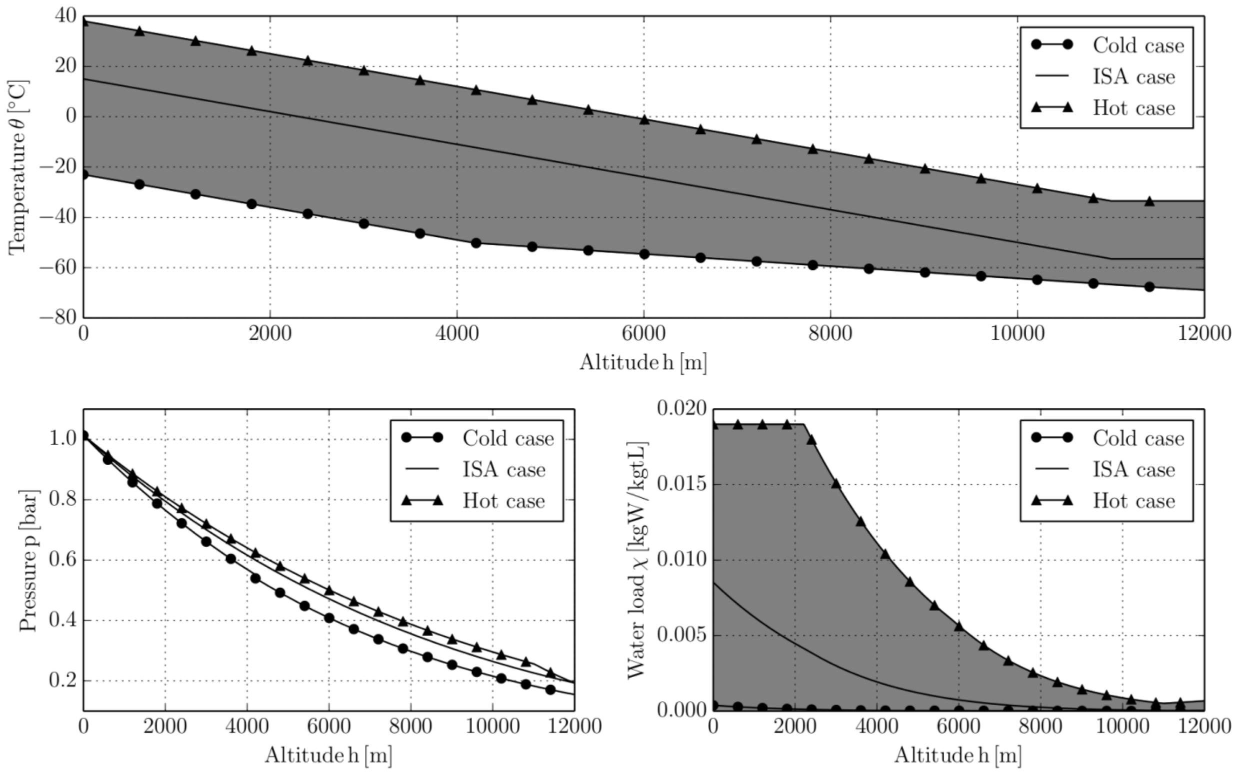


Figure 3: Ambient conditions according to the International Standard Atmosphere (International Civil Aviation Organization, 1976)

The vapor cycle machine is developed and designed as a replacement system for existing airplanes of the type Airbus A320. However the process can also be applied to other types of aircrafts. The interfaces to other subsystems cannot be changed. For this reason, the system has to be driven pneumatically via bleed air from the jet engine and the water has to be separated at high pressure. Since the conditioned air is first mixed with recirculated cabin air and then injected in the cabin, a relatively low temperature at the entry of the cabin must be reached. This can only be accomplished rationally by an air expansion turbine, because otherwise the temperature difference in the refrigeration cycle is too high and the coefficient of performance would be significantly reduced.

3. DESIGN PROCESS

Based on the ideas presented in Section 1 a new system with a vapor-compression cycle has to be developed, which can fit all the requirements shown in Section 2. The main criterion for the efficiency of this system is the possible reduction of the bleed air mass flow. Secondary criteria are the reduction of ram air mass flow and overall weight (both only in flight). But for the first concepts only the bleed air mass flow was considered because it has a 10 times higher impact on the overall efficiency of the aircraft than the ram air mass flow. The influence of the weight of the new system is difficult to regard in the first designs as the detailed dimensions of all components have to be known. The accurate weighting of the three design criteria depends highly on the regarded aircraft and the flight profile and is done internally by Airbus afterwards.

In the first step of the design process different possible processes with the use of a vapor-compression cycle are developed (in the end over 12 alternatives). Then these processes with the highest possible reduction of bleed air are chosen with the help of basic process calculations. In the next step detailed simulation models are prepared for these processes. Different system parameters, e. g. the pressure ratio of the turbine, are set by the boundary conditions. Other parameters, e. g. the pressure ratio of the refrigerant compressor, the evaporation temperature and the size of the heat exchangers, can be changed in a specific range depending on the technical feasibility and the output states, which have to be reached. The heat exchangers are modelled with a constant kA approach (heat transfer coefficient multiplied by heat exchanger area). The state changes of the turbo-machines are considered isentropic with constant polytropic efficiency.

For the calculation of all state variables and state changes of every element in the new system, a simulation model is created with the simulation tool MATLAB (MathWorks, 2013). The state variables are calculated at the inputs and outputs of all elements. The order of the calculation is given by the direction of the main flows of the system (bleed air, ram air, ambient air and refrigerant) and by the order of every component in these flows. The properties of the working fluids are taken from the program REFPROP (NIST, 2010). The components of the system (heat exchangers, turbo-machines, etc.) and all sub-functions (calculation of moist air, etc.) are each represented by a function in the MATLAB code. The calculation program is modular and can be used for stationary simulations with given boundary and ambient conditions.

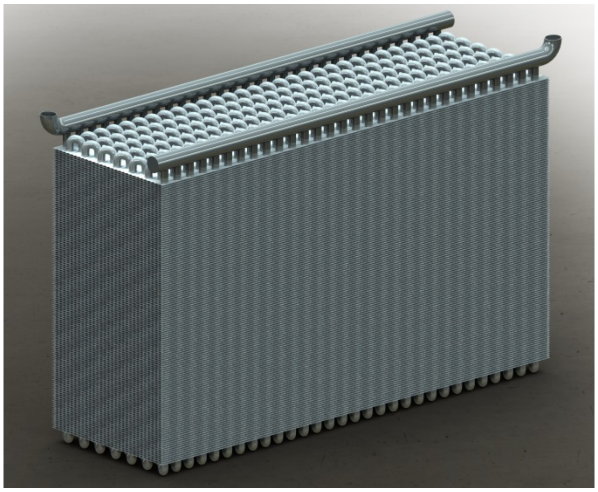
The variable parameters are changed till the reduction of bleed air mass flow reaches a maximum. Though the system is complex there are only a couple of parameters which can be varied freely in a small range. That's why the influence of these parameters can be evaluated manually by calculating all possible combinations. But the procedure is limited as only few operating cases are regarded and further influences on the whole aircraft cannot be evaluated in the model. A mathematical optimization is planned but due to the complexity not yet realized. In future studies a dynamic model for the whole operating map and the entire system with detailed performance maps of the turbo-machines and heat exchangers, as well as a control system has to be prepared in order to calculate and benchmark the process more precisely.

In the last step of the design process the calculation results of the simulation are compared with the reference system and with each other and the most efficient process is chosen. The new system is shown in Section 4 and the results are presented in Section 5.

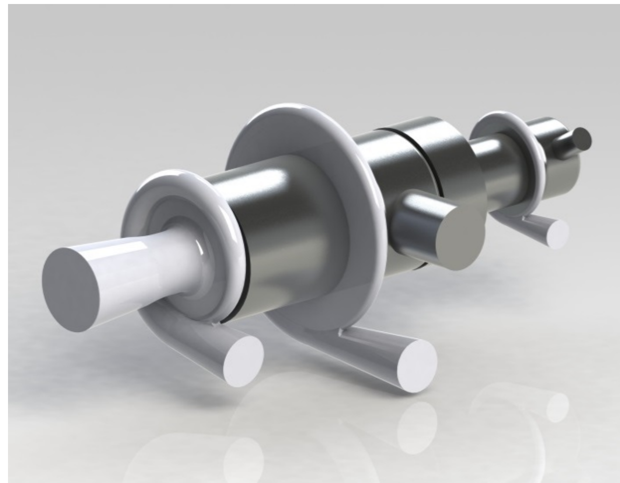
The crucial components of the environmental control system are the turbo-machines and the heat exchangers. Therefore these elements have to be designed and calculated in-depth. The design of the heat exchangers consists of two different parts. In the first part the dimensions of each heat exchanger are calculated with the knowledge of either the temperature profile or the transferred thermal energy. With the defined dimensions every heat exchanger is recalculated in the second part. For this purpose a detailed model, based on a lumped parameter method, is created.

With the help of the design study of the heat exchangers it is possible to determine the weight, pressure losses, transferred heat in every operating case and dimensions accurately. The heat exchanger dimensioning is conducted after the process simulation because the simulation results are necessary for the most input states. After the dimensioning of the heat exchangers slight changes of the system are adapted in order to reduce the overall weight. Especially the condenser has the potential for further optimizations as it is relatively large compared to the evaporators or the air to air heat exchangers. The determined pressure losses are integrated in the simulation model. In future studies the whole performance maps or the calculation routines of the heat exchangers and turbo-machines must be implemented into the process simulation as well.

The weight of the remaining components (e.g. tubes, refrigerant collector, amount of refrigerant) is obtained via a 3D model, which was created with the program SOLIDWORKS. The 3D model of the condenser and the machine set is shown in Figure 4.



(a) Condenser



(b) Machine set

Figure 4: 3D model of the pneumatically driven vapor cycle machine

4. PNEUMATICALLY DRIVEN VAPOR CYCLE MACHINE

As mentioned in the introduction, the second stage of the air cycle shall be replaced by a separated vapor-compression cycle. The basic structure of the new system is shown schematically in Figure 5.

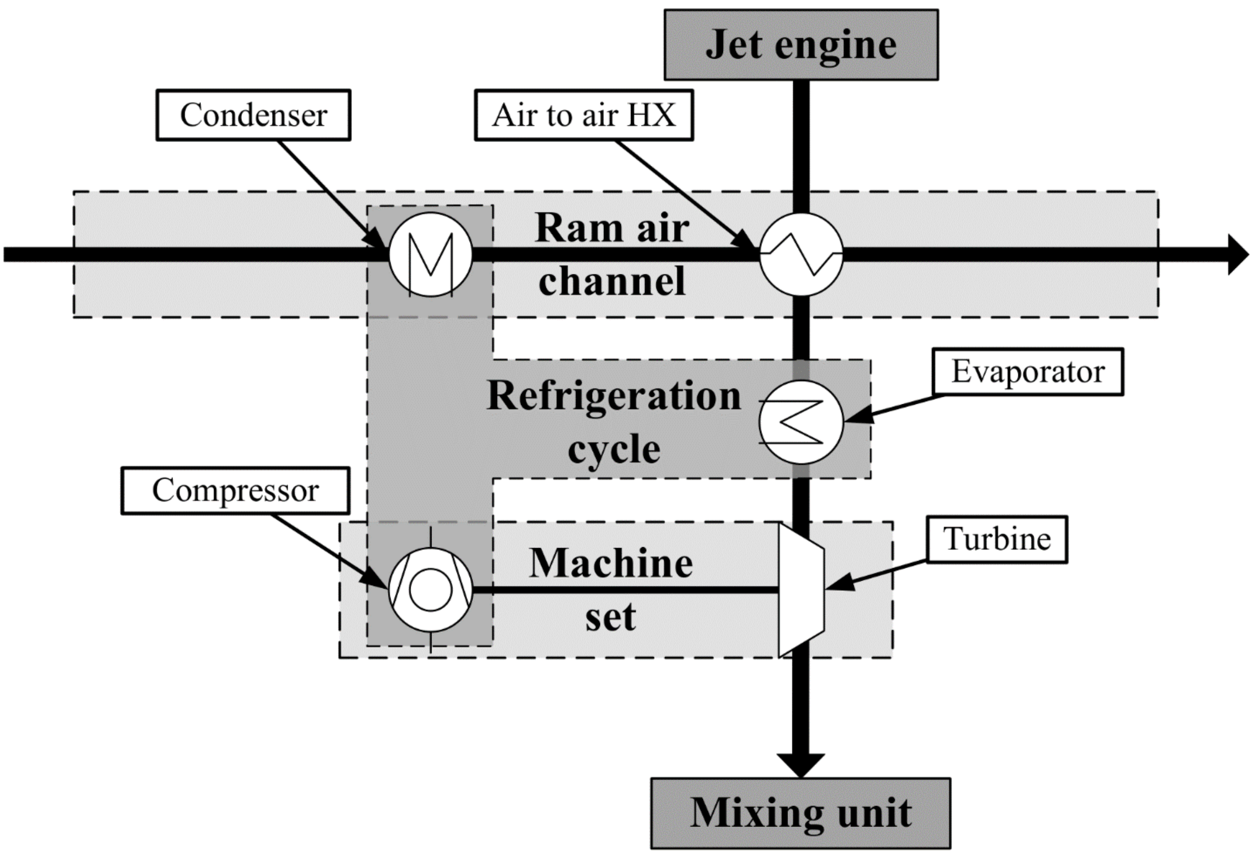


Figure 5: Scheme of the pneumatically driven vapor cycle machine for the air-conditioning of aircrafts

The bleed air from the engine is cooled by the air to air heat exchanger and the evaporator, then expanded in the turbine and finally led to the mixing unit. The evaporator is a part of the refrigerant circuit, which is based on the basic vapor-compression refrigeration. The refrigerant compressor, the air compressor and the air turbine are installed on one shaft. The condenser in the refrigeration cycle is situated in the ram air channel. According to the reference system the heat is dissipated via the ram air to the environment.
The state variables temperature θ, pressure p and water load χ for the inlet (engine conditions) and the outlet (cabin conditions) of the bleed air, as well as for the inlet of the ram air (ambient conditions) are completely defined for the air-conditioning pack according to the former chapter about boundary conditions.

5. CALCULATION RESULTS AND COMPARISON

To evaluate the new system the results of the simulation are compared with the reference system. The reference data is taken from an internal model of the currently used system. This model is also correlated with data gained by measurements. The main quantities of the system, which are influencing the overall efficiency, are the bleed air and the ram air mass flow, as well as the total weight. The weight substantially affects the fuel consumption of the entire aircraft and the ram air inlet induces an additional drag, which also decreases the overall efficiency. The bleed air taken from the jet engine is directly related to the fuel consumption, because the more mass flow is taken from the engine, the more air has to be compressed from the ambience. The impact of the bleed air mass flow to the overall efficiency is 10 times larger than the influence of the ram air mass flow. At the ground operating cases only the bleed air mass flow is considered, because the other quantities have no influence here. It is possible to connect all three quantities via a weighting function and express as a weight equivalent. This weighting function depends highly on the regarded aircraft and flight profiles; hence only the two important mass flows are compared in this study. Other influences, e. g. constructional modifications, are not considered.
The weight of the new system is about 15% higher. The percentage differences of the bleed air mass flow between the new and old system for all regarded operating cases are shown in Figure 6.

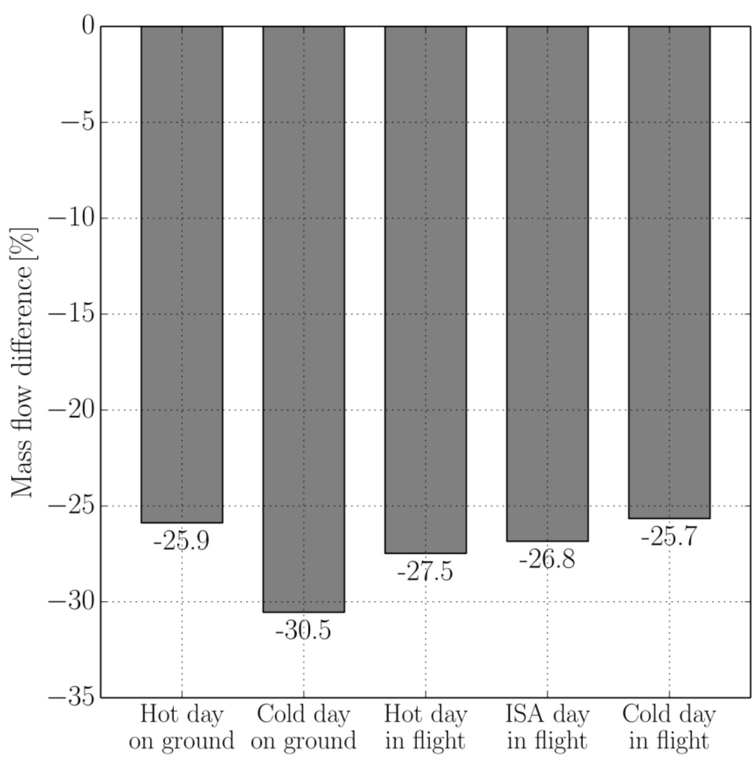


Figure 6: Mass flow difference of the bleed air for all calculated operating cases

In all five operating cases a considerable reduction of bleed air mass flow is noticeable. At the operating case "hot day on ground" a reduction of about 26 % and at the "cold day on ground" of about 31% bleed air mass flow is achieved. At the "hot day in flight" the decrease of bleed air mass flow amounts to approximately 28 %, at the "cold day in flight" to about 26% and at the "ISA day in flight" to about 27%. These results show a significant improvement compared to the air cycle machine. The ISA operating case represents the standard case in flight and occurs in about 90 % of the time during a flight profile. The percentage differences of the ram air mass flow between the new and old system for all regarded operating cases are shown in Figure 7.

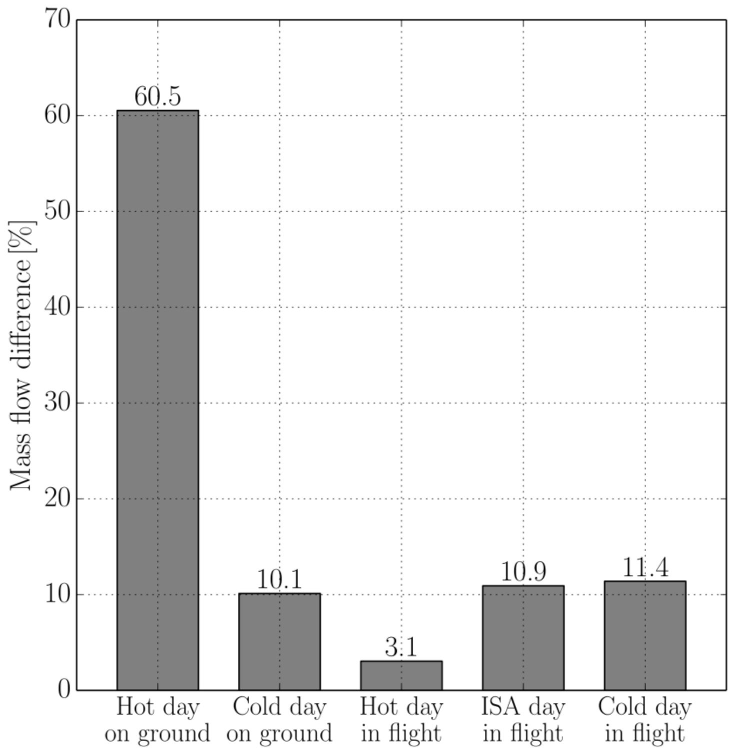


Figure 7: Mass flow difference of the ram air for all calculated operating cases

At all operating cases the increase of ram air mass flow is relatively small and therefore negligible except at the "hot day on ground". On ground the increase of ram air mass flow is irrelevant because the aircraft is not moving and there is no influence to the overall efficiency. This fact is used in the design process to reduce the weight and dimensions of the condenser. The higher the mass flow of the ram air is, the smaller the heat exchanger area can be designed. This is necessary because the temperature difference of the refrigerant and the ambient air is relatively small compared to the difference of the bleed air and ambient air. These considerations result in an increase of about 61% ram air mass flow at the "hot day on ground".

6. CONCLUSIONS AND FURTHER DEVELOPMENTS

In the feasibility study, a new approach for the air-conditioning of an aircraft using the vapor-compression cycle is investigated. At first the boundary and environmental conditions for different operating cases are defined. Afterwards a new system is developed and simulated with a self-created calculation program. The calculation results obtained from the model are compared with the currently used air cycle machine in aircrafts of the type Airbus A320. A comparison shows a significant saving of about 26 % bleed air mass flow for the reference case on ground and 28 % for the case of operation in flight, each at hot ambient conditions. Two vapor cycle machines and the machine set, which were developed in this study, were registered as a patent (Golle et al., 2013a) (Golle et al., 2013b).

The feasibility and energy-saving potential of the new environmental control system are proven in theory. In the next project phase there will be further theoretical analyzes. These include for instance the investigation of more operating cases or a continuous map, the integration of the turbo machinery and heat exchanger maps into a dynamic simulation program and optimizations of all components. Furthermore the feasibility of the vapor cycle machine has to be proven experimentally. Therefore the development of a test bench and a prototype for the verification of the calculated results and the control systems is planned.

NOMENCLATURE

Latin Letter

A	Heat exchanger area	[m²]
h	Altitude	[m]
h	Specific enthalpy	[kJ/kg]
k	Heat transfer coefficient	[W/K·m²]
p	Pressure	[bar]
s	Specific entropy	[kJ/kg·K]

Greek Letter

θ	Temperature	[°C]
χ	Water load	[kg_W/kg_{tL}]

Subscript

tL	Dry air
W	Water

REFERENCES

Airbus Operations GmbH, 2012, Pneumatically driven vapor cycle machine, Hamburg.

Federal Aviation Administration, 2013, FAA Regulations [Online], Retrieved October 10, 2013, Available: http://www.faa.gov/regulations_policies/faa_regulations/.

Golle, S., Hesse, U., Klimpel, F., 2013, Aircraft air conditioning system and method of operating an aircraft air conditioning system, EU Patent 12 194 125.6-1753, Registered January 16, 2013. .

Golle, S. et al., 2013, Aircraft air conditioning system and method of operating an aircraft air conditioning system, EU Patent 13 175 020.0-1754, Registered August 27, 2013.

International Civil Aviation Organization, 1976, ICAO Standard Atmosphere Doc 7488.

Joint Aviation Authorities, 2013, Publications Section 1 [Online], Retrieved October 10, 2013, Available: http://www.jaa.nl/publications/section1.html.

MathWorks, 2013, MATLAB Dokumentation [Online], Retrieved April 12, 2013, Available: http://www.mathworks.de/de/help/matlab/.

NIST, 2010, Standard Reference Database 23, Reference Fluid Thermodynamic and Transport Properties Database 9.0 (REFPROP), National Institute of Standards and Technology.

Skovrup, M. J., Knudsen, H. J. H., 2013, CoolPack [Online], Retrieved October 10, 2013, Available: http://en.ipu.dk/Indhold/refrigeration-and-energy-technology/coolpack.aspx.