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CABIN TEMPERATURE CONTROL MODEL FOR COMMERCIAL AIRCRAFT

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Abstract. *This paper presents a model to simulate the dynamic behavior of cabin temperature in an aircraft in the airline market. The model includes the most important components in Environmental Control System (ECS) mainly the air conditioning packs and packs bypass valves. The model predicts the cabin temperature in the aircraft which may fly in several operating conditions. Some case studies are presented and the results are compared to experimental data collected in a similar aircraft. It was found a good agreement between results predicted by the model and the experimental data. The simulation model may be used to evaluate the cabin temperature control and to improve the components design and the performance of ECS under transient conditions. Based on this analysis the ECS controller may be designed to improve the response time and the cabin temperature control stability.*

Keywords: *model, cabin temperature, control.*

NOMENCLATURE

A	Valve maximum area
c	Concentration of chemical species
C	Capacitance
Cp	Specific heat
Cv	Mass flow coefficient for ram air
D	Manifold equivalent diameter
dp	Pressure drop in bleed manifold
Ef	Compressor or turbine efficiency
kt	Thermal conductivity
K	Valve discharge factor
h	Convection heat transfer
L	Manifold equivalent length
$\dot{m}$	Mass flow
$\dot{m}_g$	Humidity generation per passenger
N	Number of occupants on board
M	Mach number
Nu	Nusselt number
P	Pressure
Pr	Prandtl number
PR	Pressure ratio compressor or turbine
$\dot{Q}_{eq}$	Heat generation by equipment
$\dot{Q}_g$	Heat generation per passenger
$\dot{Q}_{rad}$	Heat flux by solar radiation
$\dot{Q}_{loss}$	Heat flux through fuselage skin
T	Temperature
U	Global heat transfer coefficient

w	Absolute humidity

1 Subscript

1	cockpit
2	cabin
3	under floor region
g	generation
b	bulk
c	cold stream
_c	compressor
CO_2	carbon dioxide
h	hot stream
mix	mixing point
mixer	mixer outlet
in	inlet
inf	air Inflow
out	outlet
p	air condition pack
pbv	pack bypass valve
recirc	recirculation fan
_t	turbine
w	wall

1. INTRODUCTION

The ambient conditions inside cabin as temperature and humidity play a key role in the passenger comfort in aircraft of airline market. However passengers ambient may be strongly affected by external ambient conditions and aircraft operations conditions.

The external ambient conditions may be extreme as winter with very cold temperatures or summer with very hot temperatures, ambient with humidity or dry air with dust or not. The ambient conditions with high dust concentration may affect pack heat exchanger performance because contamination in ram air inflow reduces the heat exchanger effectiveness.

The operating conditions in airlines may vary a lot and affect differently the passengers comfort. Variations on engine regime and flight altitude affect the bleed conditions. Also variations on the number of passengers on board, ambient temperature, aircraft configuration may affect the heat load and heat dissipation in the aircraft.

This paper presents Simulink model to simulate the Cabin Temperature Control (CTC) for an aircraft in airline market and analyze the dynamic behavior of Cabin Temperature in several operating conditions. The CTC model includes the most important components in Environmental Control System (ECS), mainly the air conditioning packs and pack bypass valves.

Several papers were published to analyze the passengers ambient in the cabin during revenue flights. He and Zhao[1] presented simulation for air conditioning pack in an aircraft based on computer model developed to assist engineers with the design and development of ECS dynamic optimization. Hoffman[2] presented cabin temperature model simulation based on coupling of existing subsystem models and compared the results to the results obtained in CFD analysis. Karlsoon[3] presented simulation model to study ECS which is divided in three sections: air supply, air conditioning and air distribution. Kremer[4] presented simulation for cabin model with one zone and compared results to the results provided by CFD simulation. Kwiatkowski[5] presented a model based on development of library of ECS components and compared the results. Nakashima[7], Scholz[8] and Ziegler[9] developed dynamic analysis using Computational Tooling to model not only the air conditioning packs, but all components Environmental Control System.

The cabin model is a thermal system in which the storage and flow of heat are involved. Thermodynamics laws shows there are only two types of passive thermal elements: thermal capacitance and thermal resistance. Strictly speaking, thermal capacitance and thermal resistance are characteristics associated with bodies that are distributed in space. However, the dynamic behavior of thermal systems may be described by lumped models[10] [11]. A greater degree of approximation is often necessary to represent a thermal system by a lumped-element model. The elements of a system are the individual components. It is known if the system elements can be lumped, the differential equations will be ordinary differential equations and if the elements are distributed, partial differential equations will be required.

The Cabin Temperature Control model (CTC) is based on one-dimensional equations andmass and energy conservation equations and includes ECS components as resistances or capacitances. Some components as pack components (compressor, turbine, fan, heat exchangers) are described by Simulink functions. Each aircraft zone is considered a capacitance, the fuselage and thermal insulations are considered resistances to heat transfer.

2. METODOLOGY FOR MODEL DEVELOPMENT

MATLAB ® and the package Simulink developed by Mathworks provide a graphical user interface (GUI) for building system models and executing the simulation. The models are constructed by drawing interconnected blocks that represent the algebraic and differential equation that describe the system behavior, similar to a block diagram. MATLAB is used in a supporting role to initialize parameter values and produces plots of system response.

Figure 1 shows typical Environmental Control System Architecture in which engines provides bleed source for air conditioning system and ice protection system. Engine bleed feeds air conditioning packs and the modulation of pack bypass valves allow to control the inflow temperature to each zone in order to achieve the zone temperatures selected by crewmembers. The bleed air consumption for ice protection system is not directly included in CTC, but the effects on pressure and mass flow are included in manifold bleed block.

Figure 2 shows how CTC model manages the ECS components blocks. The structure of CTC model is comprised by several blocks: bleed manifold, air conditioning packs, bypass valve, mixing point, mixer, recirculation fans, mixer, cabin, ECS Controller.

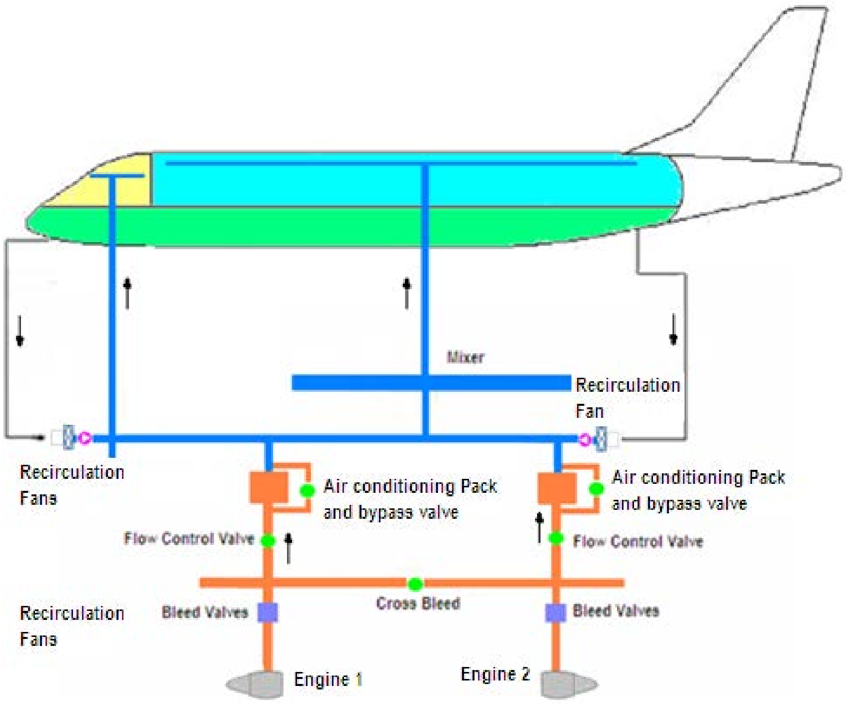

Figure 1: Typical ECS Architecture for aircraft in Airline Market

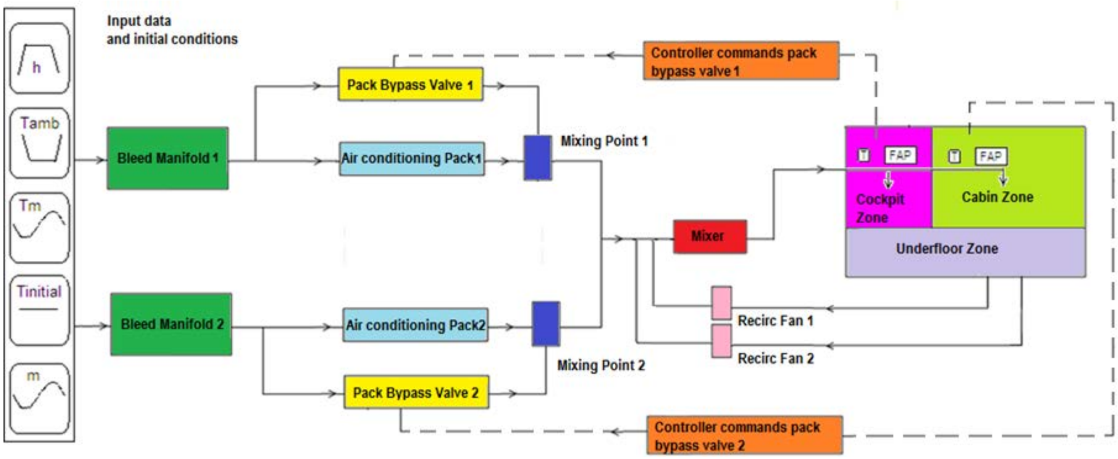

Figure 2: Structure of Cabin Temperature Control Models

The air conditioning pack block is the most complex in CTC which use air cycle machine (ACM) with three rotors: fan, compressor and turbine. The three rotors turn axially as one assembly. The turbine rotor is on one end, the cooling fan is on the other end and the compressor rotor is between them.

The ram air circuit does not have air inflow modulation and the ram air flow in flight depends basically on ram air geometry, ambient conditions and aircraft speed.

The Cabin temperature Control model CTC consists of the following main blocks: bleed manifold, air conditioning pack, pack bypass valve, pack and bypass valve mixing, mixer, cabin and controller.

A. BLEED MANIFOLD MODEL

The bleed manifold provides air source to air conditioning packs. Since the length of bleed tubes from engines to air conditioning packs is long, the temperature and pressure decreases from engines to air conditioning packs. The heat loss and pressure drop is calculated according to equations (1) thru (4).

The heat loss from wall tubes to external ambient is basically by convection. The heat transfer coefficient for convection is given by empiric Dittus-Boelter correlation[12]:

$$Nu = 0.023.\mathrm{Re}^{0.8}.\mathrm{Pr}^{0.3} \qquad (1)$$

It is shown that heat loss from bleed tubes depends on Reynolds and Prandtl and the temperature difference between bulk temperature (T_{bulk}) and wall temperature (T_w).

The heat loss from bleed manifold tubes is given by:

$$\dot{Q} = h.A.(T_w - T_b) \qquad (2)$$

The convection heat transfer coefficient (h) depends on Re, Pr and duct diameter.

The heat loss from bleed tubes is calculated based on bleed temperature at manifold inlet and length and material of bleed tubes. The bleed temperature at manifold outlet is then calculated.

The bleed air pressure drop is calculated by based in the pressure drop factor[8]:

$$dp = \varepsilon \frac{1}{2} \rho.V^{2} \quad \varepsilon = \lambda \frac{L}{d} \qquad (3)$$

For turbulent flows, the relation according to Scholz[8] is:

$$\lambda = 0.316.\mathrm{Re}^{-0.25} \tag{4}$$

B. AIR CONDITIONING PACK MODEL

The air conditioning pack model includes the main components: ram air inlet, primary heat exchanger, compressor, secondary heat exchanger, condenser, re-heater and turbine. The water collector and short pack tubes which interconnect pack components are not considered since there is no significant thermal effect in these components.

Figure 3 shows the components of air conditioning pack. In sequence it will be described the main structure of air conditioning pack components: air cycle machine (ACM), primary and secondary heat exchanger, condenser, re-heater, water collector and ram air. ACM comprises fan, compressor and turbine assembly.

The Cabin Temperature Control model (CTC) consists of the following main blocks: bleed manifold, air conditioning pack, bypass valve, pack, mixing point, mixer, cabin and controller.

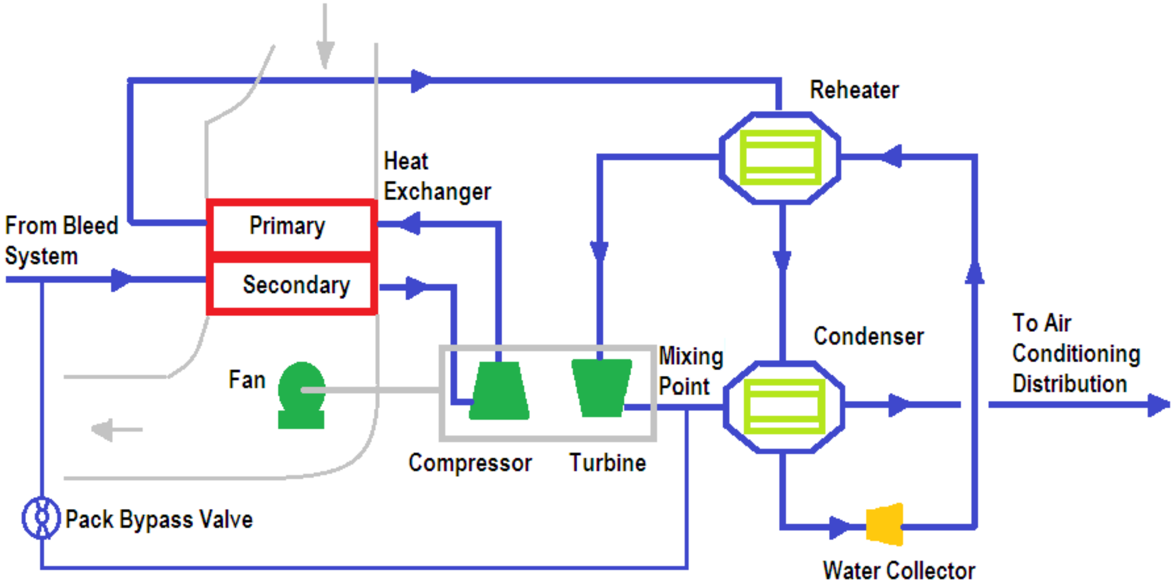

Figure 3: Air Conditioning Pack Components

Engines provide bleed to air conditioning packs. The bleed enters the primary heat exchanger where it is cooled by ram air flow and then goes to the compressor. Air from the compressor of the Air Cycle Machine (ACM) goes through the secondary section of the dual heat exchanger where it is cooled again. The air then goes into the condenser inlet. The condenser core decreases the temperature of the air. Airflow through the mixer section removes some of the heat from the core. The decreased temperature and the increased pressure cause the condensation of water that is in the air. The water then flows to the water collector and out through the water drain. The water flows to a nozzle that applies a spray of water to the ram-air inlet duct of the heat exchanger. Cold air from the turbine section of the ACM flows into the mixing point where is mixed to air coming from pack by pass valve. The mixed air is warmer than the air from the ACM. Air in the mixer section then flows through the core of the condenser section. In the core, it gets some more heat from the core. The air then goes to the cabin distribution system.
The water collector is installed downstream condenser where it removes the water produced. A spray nozzle removes the water accumulated at the bottom of the collector and discharges in heat exchanger inlet.

B.1 COMPRESSOR MODEL

The air cycle machine compressor has complex dynamic behavior however according to He and Zhao[1]the compressor model may be simplified and compressor outlet temperature depends basically oncompressor pressure ratio (PRc) and compressor efficiency (Efc).
Based on Gas Dynamics Equations, the compressor inlet and outlet temperatures are related by the following:

$$T_{c\_out} = T_{c\_in} * \left(\frac{PR_c^{\,0.286} - 1 - Ef_c}{Ef_c} \right) \tag{5}$$

B.2 TURBINE MODEL

In similar way to compressor model, the turbine model may be simplified according to He and Zhao[1]and compressor outlet temperature depends basically on compressor pressure ratio (PRt) and turbine efficiency (Eft). The turbine inlet and outlet temperatures are related by the following:

$$T_{t\_out} = T_{t\_in} * \left(1 - Ef_t \left(1 - \frac{1}{PR^{0.286}} \right) \right) \tag{6}$$

B.3 FAN MODEL

The fan of air cycle machine pulls air from ambient to ram air and to heat exchanger during ground operation to cool down the engine bleed which passes through heat exchanger. The ram air flow depends on fan performance charts and CTC includes the flow maps in look up tables for ram air operation on ground. The mass flow maps depend on ambient temperature and pressure.

In flight the impact air passes through fan bypass check valve and goes to heat exchanger. In flight the airflow is calculated according to ram air model

B.4 HEAT EXCHANGERS MODEL

The CTC model utilizes for heat exchangers in the air conditioning packs the concept of heat exchanger effectiveness. The Heat Exchanger model uses the effectiveness method.

The energy balance in heat exchanger for cold and hot streams provides the following equations[12]:

$$\dot{m}_h \,.(T_{hin} - T_{hout}) = \dot{m}_c \,.(T_{cin} - T_{cout}) \tag{7}$$

$$\varepsilon = \frac{T_{hin} - T_{hout}}{T_{hin} - T_{cin}} \text{ or}$$

$$\varepsilon = \frac{T_{cin} - T_{cout}}{T_{hin} - T_{cin}}$$

The Primary and Secondary Heat Exchanger, Condenser and Re-heater are cross-flow heat exchanger with both fluids unmixed. The energy balance written for assembly of two stream yields.

B.5 RAM AIR MODEL

The ram air circuit is shown in Figure 3. The air is collected from ambient to ram air inlet and used to cool the bleed that goes to air conditioning packs.

The ram air airflow is collected from ambient through NACA inlet and the mass flow according Perez[13] is evaluated depending on ambient density, aircraft speed and NACA inlet area Ai:

$$\dot{m}_r = \rho.V.A_i = \frac{Pa}{R.T_a}.M.\sqrt{\gamma.R.T_a}.A_i \tag{8}$$

For given set of flight conditions: altitude (h) and flight Mach number (M), outside air conditions (Ta and Pa), it is possible to calculate the ram air flow. The airflow in NACA inlet is corrected by mass flow coefficient (Cv) based on experimental data which is included in ram air mass flow calculation.

C. PACK BYPASS VALVE MODEL

The pack bypass valve is modeled as an orifice. The mass flow through an orifice is given by according to Karlsson[3]:

$$\dot{m}_r = \frac{A.P_u}{\sqrt{R.T}}.K(P_u / P_d) \tag{9}$$

The mass flow depends basically on orifice area, upstream pressure and valve discharge coefficient K. The discharge coefficient depends on valve geometry and is given by curve shown in Figure 4.

The ECS valves are typically butterfly valve type. A butterfly valve consists of a circular disc on a shaft mounted in the center of a duct. The effective area of the valve is calculated by measuring the position of the shaft.

The effective area of pack bypass valve is function of opening angle:

$$A_{eff} = A_{o.}.(1 - \cos\theta) \tag{10}$$

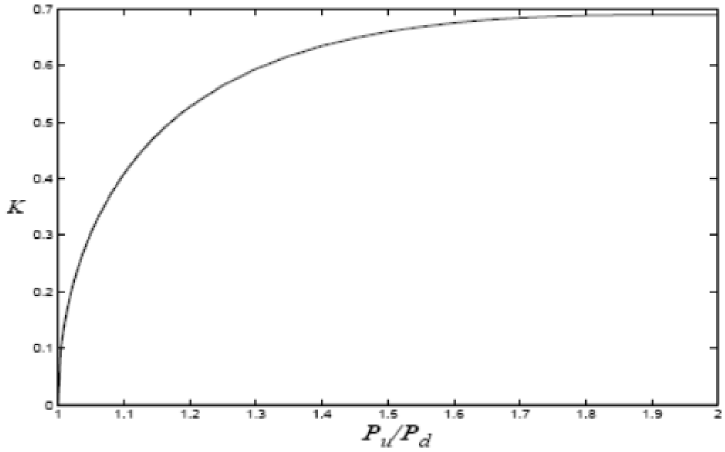

Figure 4: Geometric Factor for butterfly valve[3].

D. MIXING POINT MODEL

The point in which pack by pass flow and pack flow are mixed is called mixing point as shown in Figure 2. The model for mixing point is based on energy balance: inlet energy is equal to outlet energy.
The mixer model is similar to mixing point model and also uses the energy balance. The function of mixer is to mix airflow coming from recirculation fan and airflow coming from packs.

The model for pack and pack bypass valve mixing also consider the mass and energy conservation equations and provides:

$$\dot{m}_{pack}.C_p.T_{pack} + \dot{m}_{pbv}.C_p.T_{pbv} = \dot{m}_s.C_p.T_s \tag{11}$$

At similar way the model considers the mixing of pack flow and recirculation fan flow. Based on mass and energy conservation equations, the following equation is obtained:

$$\dot{m}_s.C_p.T_s + \dot{m}_{recirc}.C_p.T_{recirc} = \dot{m}_{mix}.C_p.T_{mix} \tag{12}$$

The mixer receives air from air conditioning pack and from recirculation fans. The mixer model which utilizes the mass and energy conservation equations provides:

$$(M.C_p)_{mixer}.\frac{dT_{mixer}}{dt} = (\dot{m}_{mix}.C_p.T_{mix})_1 + (\dot{m}_{mix}.C_p.T_{mix})_2 - \dot{m}_{mix}.C_p.T_{mixer} \tag{13}$$

The product $(M.Cp)_{mixer}$ corresponds to mixer capacitance.

The mixing point temperature is determined based on energy balance: the outlet enthalpy flux is the sum of enthalpy fluxes coming from pack and pack bypass valve:

$$\dot{m}_{pack}.C_p.T_{pack} + \dot{m}_{pbv}.C_p.T_{pbv} = \dot{m}_s.C_p.T_s \tag{14}$$

Considering air as perfect gas, the enthalpy flux is the product of specific heat coefficient times airflow.Downstream mixing point, it occurs mixing of air coming from pack outlet and air from recirculation fan. The mixing temperatureis calculated by:

$$\dot{m}_s.C_p.T_s + \dot{m}_{recirc}.C_p.T_{recirc} = \dot{m}_{mix}.C_p.T_{mix} \tag{15}$$

E. RECIRCULATION FAN MODEL

The recirculation fans are used to provide power to air for cabin recirculation. The fans pulls air from recirculation bay under-floor and force air back to cabin. The recirculation fan model is calculated based on fan mass flow map.

F. MIXER MODEL

The mixer of air conditioning distribution receives air from air conditioning packs and recirculation fans.The mixer model uses mass and energy conservation equations to calculate the mixer outlet temperature which is given by:

$$(M.C_p)_{mixer}.\frac{dT_{mixer}}{dt} = (\dot{m}_{mix}.C_p.T_{mix})_1 + (\dot{m}_{mix}.C_p.T_{mix})_2 - \dot{m}_{mix}.C_p.T_{mixer} \tag{16}$$

The product $(M.Cp)_{mixer}$ corresponds to mixer capacitance which is not negligible since mixer volume is not negligible. The entalpy for airflow inlet from pack and recirculation fan for left side is $(M.C_{p.}T_{mix})_1$ and for right side is $(M.C_{p.}T_{mix})_2$.

G. CONTROLLER MODEL

The aircraft temperature controller commands the pack bypass valves for pack 1 and pack 2 in order to achieve the required inflow temperatures in cockpit and cabin zones (zones 1 and 2).

The cabin temperature control shall provide response of cabin temperature for normal aircraft operating conditions. In order to optimize the controller performance, the following requirements will be requested: settling time lower than 1500 s, overshoot lower than10%, rise time lower than 1000s and steady-state error lower than 5%.

The control actions for pack bypass valve are based on difference between reference temperature and zone temperature and this difference will be used to calculate the inflow temperatures for zones 1 and 2. In order to achieve the calculated inflow temperatures, it is calculated the flow mass through pack bypass valve.

The mass flow through pack bypass valve is obtained by equation:

$$\dot{m}_s.C_p.T_s + \dot{m}_{recirc}.C_p.T_{recirc} = m_{i_1}.C_p.T_{i_1} \tag{17}$$

The cabin temperature controller controls the pack bypass valve from pack 1 and pack 2 in order to reach the duct temperatures required to achieve the zone temperatures selected in flight attendant panels: cockpit and cabin zone temperatures.

The CTC model uses PID block available in Simulink Library to perform the function of ECS Controller. This block performs the function of proportional, integral and derivative Controller (PID) and it is available in Simulink Library.

The controller parameters are Kp, Ki and Kd and shall be optimized in order to achieve the stabilization of selected temperature in each zone. The Control System Tools available in Simulink can provide automatic optimization of Kp, Ki and Kd parameters to comply with ECS Controller performance requirements.

It is known an increase of parameter Kp decreases rise time, the increase of Ki decreases the rise time and steady state error and increase of Kd decreases overshoot and increases stability temperature. It was noticed in CTC Simulations, the Ki close to zero produces reduction of stabilization time.

The Controller will command pack bypass valve based on difference between temperature selected by flight attendants in each zone (Tref) and the actual temperature in the zone. This difference is called temperature error and it is utilized by controller to calculate the air inflow temperature to each zone.

In summary, it is necessary to calculate the required mass flow through pack bypass valve to provide the air inflow temperature to each zone as calculated previously. In this way, CTC model calculates the opening area and opening angle to bypass valve produce the calculated mass flow.

The control logic calculates the inflow temperature to cockpit and then the mass flow through pack bypass valve #1 or left hand side valve. In similar way it is calculated the inflow temperature to cabin and then the mass flow through pack bypass valve #2 or right hand side valve. The mass flow in bypass valve defines the valve opening area and consequently the valve opening angle required to achieve the temperature reference in each zone.

The mass flow in pack bypass valve which produces the required air inflow temperature is given by the equation derived from mass and energy conservation:

$$f_1.\left[\dot{m}_{mix}.C_p.T_{mix}\right]_1 + f_2.\left[\dot{m}_{mix}.C_p.T_{mix}\right]_2 = \dot{m}_{i_2}.C_p.T_{i_2} \tag{18}$$

H. CABIN MODEL

The aircraft is divided in three zones for Cabin Temperature analysis: cockpit zone, cabin zone and under floor zone according to Figure 5.The mass of Interior parts like seats, carpet, cabinets, panels, luggage, monuments and system equipment represent the mass around cabin and cockpit and that affect the time to cool or heat the cabin and cockpit. These parts in lumped analysis contribute to capacitance of each zone C_1, C_2 and C_3.

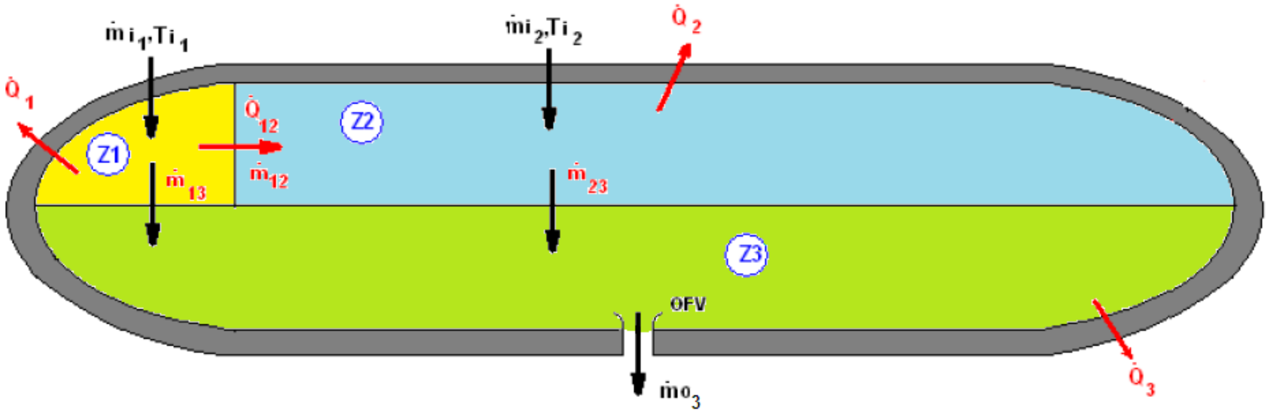

Figure 5: Cabin Model

Based on mass and energy equations conservation it is possible to calculate the zone temperatures.

Zone 1 – cockpit:

$$C_1.\frac{dTz_1}{dt} = \dot{m}i_1.C_p.Ti_1 - \dot{m}o_1.C_p.T_{z1} - \dot{Q}_{12} - \dot{Q}_{loss\_fuselage\_1} + \dot{Q}_{occup\_1} + \dot{Q}_{equip\_1} + \dot{Q}_{solar\_rad\_1} \quad (19)$$

Zone 2 –cabin:

$$C_2.\frac{dTz_2}{dt} = \dot{m}i_2.C_p.Ti_1 - \dot{m}o_2.C_p.Tz_2 + \dot{Q}_{12} - \dot{Q}_{loss\_fuselage\_2} + \dot{Q}_{occup\_2} + \dot{Q}_{equip\_2} + \dot{Q}_{solar\_rad\_2} \quad (20)$$

Zone 3 – under-floor region:

$$C_3.\frac{dTz_3}{dt} = \dot{Q}_{13} + \dot{Q}_{23} - \dot{m}o_3.C_p.Tz_3 - \dot{Q}_{loss\_fuselage\_3} + \dot{Q}_{equip\_3} \quad (21)$$

It is noticed the temperature in each zone depends on enthalpy fluxes at inlet and outlet, heat loss from each zone, heat generation by occupants, electrical equipment and solar radiation. The skin heat loss is calculated based on global Heat Transfer Coefficient which includes conduction and convection heat transfer.

Figure 6 shows the cabin model which is based on equation (20). The equations (19) thru (21) are the base for the three aircraft zones. The zone temperatures are function of zone capacitance and heat fluxes in each zone. In a similar way, the model evaluates the humidity and carbon dioxide concentration inside the cabin using equations (22) and (23).

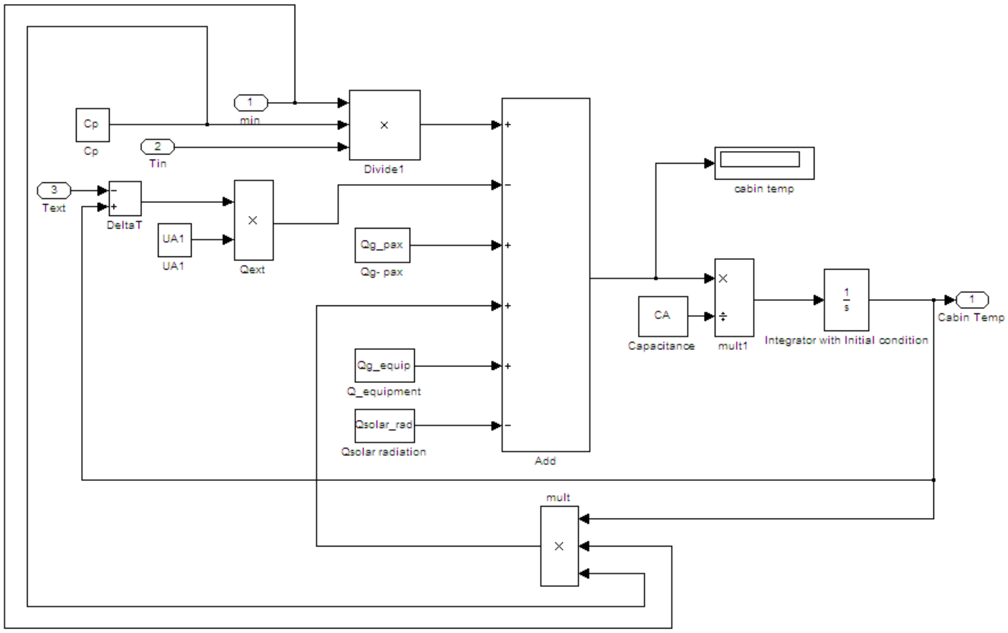

Figure 6: Cabin Model

The cabin model also includes the humidity and CO_2 concentration analysis in the cabin. The passengers are the main contributor for humidity and CO_2 generation on board.

The cabin humidity depends on humidity of fluxes at cabin inlet and cabin outlet and the humidity generation from passengers and crewmembers. The humidity balance produces:

$$m_c \frac{dw_c}{dt} = \dot{m}_e . w_e + \dot{m}_{w\_pax} - \dot{m}_s . w_c \tag{22}$$

The cabin CO_2 concentration depends on CO_2 concentration of fluxes at cabin inlet and cabin outlet and CO_2 generation from passengers and crewmembers. The CO_2 balance produces:

$$\frac{dC_{co_2\_cab}}{dt} = v_{in} . C_{co_2\_in} + N \, \dot{m}_g - v_{out} . C_{co_2\_cab} \tag{23}$$

Experimental data are not available to validate the results for humidity and gases during flight at several operating conditions.

3. INITIAL CONDITIONS AND INPUTS

The process of modeling dynamic systems involves the formulation of the differential equations including the initial conditions and inputs. The proper identification of initial conditions and inputs is something a difficult task requiring a considerable amount of technical decision making.

It is possible to simulate the whole flight or part of flight. It is necessary to provide time history of altitude, ambient temperature, bleed conditions for the whole flight. The environmental Conditions are provided by ISA block from Simulink and it is possible to associate ambient temperature to the altitude for the whole flight. In the troposphere, if flight altitude increases, the ambient temperature decreases. Above 11.000 m, the air temperature maintains at -56.5^0 C. The flow mass from engines and pressure and temperature of engine bleed may be provided as input functions or look-up tables.

4. SIMULATION AND RESULTS

Some study cases were simulated with CTC model considering several ambient conditions, flight altitude, engine regime, passenger load on board, equipment heat loads. The results are compared to flight data from aircraft in airline market.

Three case studies are presented and the results are compared to experimental data collectedinasimilar aircraft. The simulation model may be used to evaluate the Cabin Temperature Control and to improve the design and the performance of ECS in transient conditions. Based on this analysis the ECS controller may be designed to improve the system response time and the Cabin Temperature Control Stability. The design and reliability of Air Conditioning System depends on full understanding of dynamic behavior of ECS components.

- Primary Heat Exchanger effectiveness: 0.8
- Secondary Heat Exchanger effectiveness: 0.8
- Compressor efficiency: 0.85
- Turbine efficiency: 0.85
- Compressor Pressure Ratio: 1.5
- Turbine Pressure Ratio: 1.5
- Recirculation Fans flow: 0.28 Kg/s
- Gases Constant R: 287KJ/Kg
- Air Specific Heat Cp: 1000 KJ/Kg K

The CTC model parameters were refined based on experimental data to obtain representative values for Fuselage skin Heat loss, zone capacitances due to cabinets, monuments and interior parts. After parameters refinement it was possible to provide good evaluation of cabin temperature in several pull-down scenarios.

The simulation in all test cases used the solver Dormand-Prince and time variable step. Increasing time step reduce the simulation time, however time step too big may produce numerical oscillations which does not represent the physical of the system behavior.

The desired cabin temperature may be selected by crewmembers through flight attendant panel (FAP) which is typically in the range 18^{0}C – 29^{0}C.

The time required to reach the reference temperature depends basically on: zone volume, initial temperature inside zone and selected temperature for this zone, maximum mass airflow.

Three test cases are analyzed by CTC model. The first test case is the simulation of cockpit and cabin heating, the second test case is the simulation of cockpit and cabin cooling and the third test case is the simulation of pull-down in an aircraft in hot soak.

Table 1: Input data for CTC Simulations

Parameter	Test Case#1	Test Case#2	Test Case#3 (pull-down)
Tcockpit (Tref)	302 K	302 K	291 K
T cabine (Tref)	302 K	302 K	291 K
Tcockpit_initial (Tinit)	297 K	291 K	311 K
Tcabine_initial (Tinit)	297 K	291 K	309 K

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Mach	0.75	0.75	0
External ambient temperature	223K	223K	311K
Altitude	37kft	37kft	Ground

For Test Case#1, the simulation considered the following scenario: aircraft in flight, flight altitude 37kft, Mach 0.75, ambient Temperature -50^{0}C, the cockpit and cabin temperatures are selected to 18^{0}C. The initial conditions are cockpit and cabin at 24^{0}C.The results are shown in Figures 7. Flight data correspondent to this test case is shown in Figure 8. Figure 8 shows test data for an aircraft at same flight conditions as Figure 7 for commercial aircraft at same operational conditions. The results shown rise time is around 15 minutes, which the time predicted by CTC model. In order to protect manufacturer intellectual property rights, the flight test data are shown in percentage representations based on reference percentage.

For Test Case#2, the simulation considered the following scenario: aircraft in flight, flight altitude 37kft, Mach 0.75, ambient Temperature -50^{0}C, the cockpit and cabin temperatures are selected to 29^{0}C. The initial conditions are cockpit and cabin at 18^{0}C. The results are shown in Figure 9. Flight Data correspondent to this test case is shown in Figure 10. Figure 10 shows test data for an aircraft at same flight conditions as Figure 9 for commercial aircraft at same operational conditions. The results shown rise time is around 15 minutes, which the time predicted by CTC model.

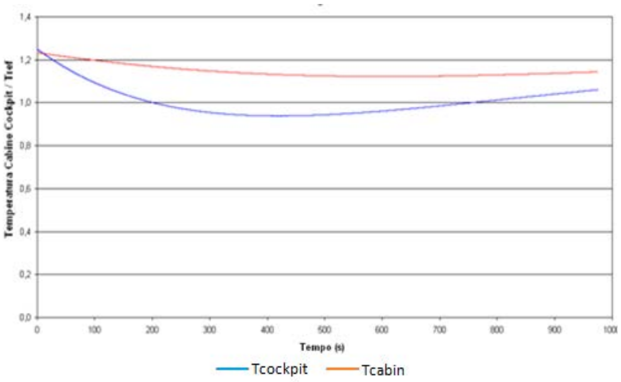

Figure 7: Temperature evolution in cooling mode simulation - Test case#1

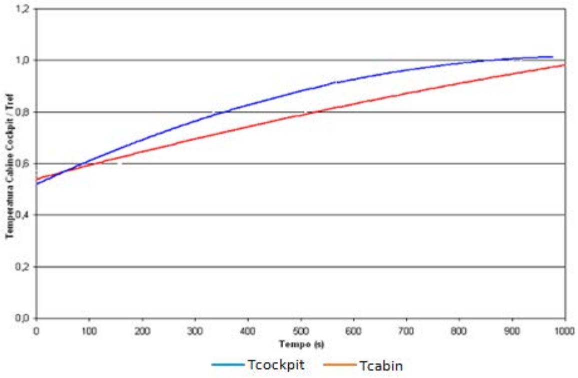

Figure 9: Temperature evolution in heating mode simulation - Test case#2

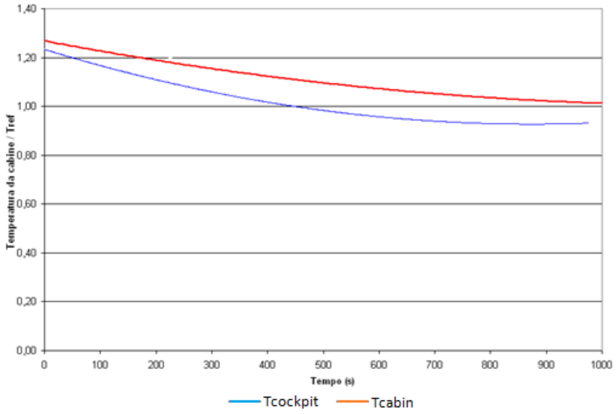

Figure 8: Temperature flight data in cooling mode - Test case#1

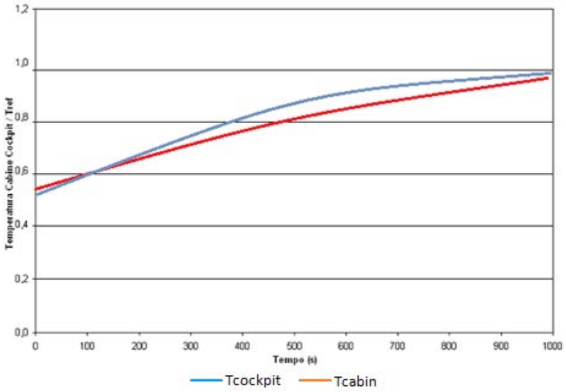

Figure 10: Temperature flight data in heating mode – Test case#2

Test Case#3 analyzes the aircraft pull-down time requirement. Pull-down time requirement is basically the time required to cool an aircraft in hot soak prior the take-off. The Air Conditioning system in airline market should be able to:

- Cool aircraft to 23 ^{0}C in 20 minutes. Pull-down time required by airlines consider on ground, no passengers, doors closed, APU bleed.
- Heat cabin of a cold soaked aircraft to +21^{0}C in 20 minutes. Pull-up time required by airlines consider on ground, no passengers, doors closed, APU bleed.

In Test Case#3, it was simulated the pull-down conditions for an aircraft submitted to hot soak in a very hot day, ambient temperature around 40^{0}C. The simulation results are shown in figure 11 for an aircraft in airline market submitted to hot soak in hot day. The pull-down time predicted by simulation is around 20 minutes which corresponds to experimental data. Figure12 shows pull-down test data for commercial aircraft with equivalent size and it is seen good agreement between results.

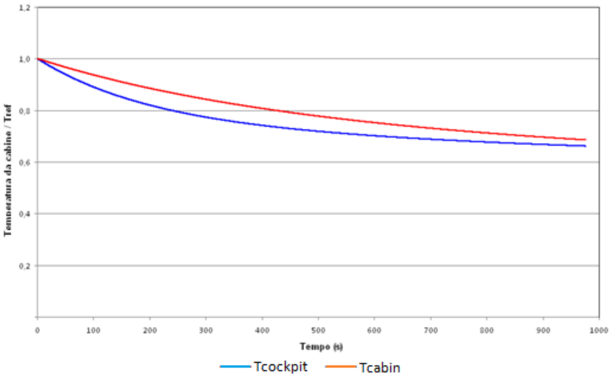

Figure 11- Temperature evolution in pull-down simulation – Test Case #3

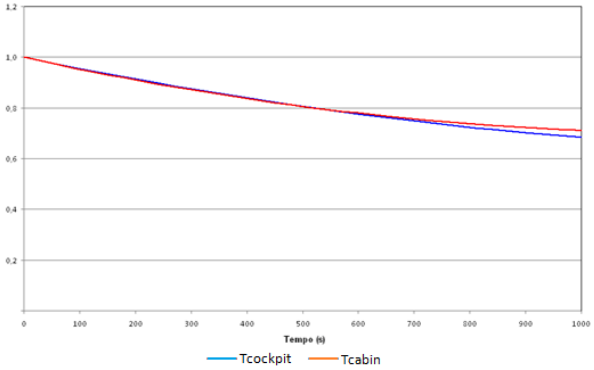

Figure12: Temperature flight data in pull-down – Test Case #3

Figure 13 provides information about temperature in several points inside the air conditioning pack: compressor inlet, compressor outlet, turbine inlet and condenser inlet. The operating conditions are important to analyze the possibility of ice formation in several parts of pack which may cause rotor unbalance and increase of blade load and consequently the possibility of blade crack by fatigue.

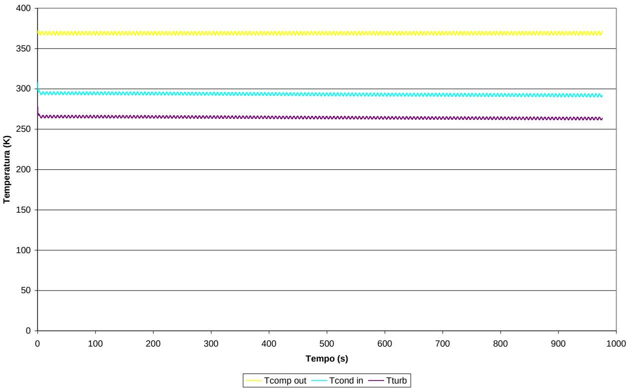

Figure 13: Temperature of pack components in heating mode

5. CONCLUSION

The simulation results provided good prediction for cabin temperature and rise time when compared to experimental data for test cases analyzed in this paper. The CTC model parameters were refined based on experimental data to obtain representative values for fuselage skin heat loss, zone capacitances due to cabinets, monuments and interior parts. CTC model provided good evaluation of cabin temperature in the test cases analyzed in this paper: aircraft cooling in flight, aircraft heating in flight and pull-down scenarios.

The CTC model may analyze the dynamic behavior of temperature in several aircraft zones and define the most important parameters to ECS architecture to provide thermal comfort to passengers.Model CTC provides parametric analysis to evaluate the performance of ECS controller and to improve components design to provide good transient behavior in different ambient conditions and operational conditions

New development may be implemented in CTC model to include dynamic behavior of bleed valve which depends on engine regime during flight. It may be also included flow control valve and trim valve dynamic to adjust the flow and temperature in the cabin.

The CTC model may be also complemented to perform full analysis of humidity and gases (CO, CO2) in several operating conditions.

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