DETERMINATION OF THE OUTFLOW VALVE OPENING AREA OF THE AIRCRAFT CABIN PRESSURIZATION SYSTEM

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Abstract. *The cabin pressure control system continuously monitors the ground and flight modes of the airplane (climb, cruise, or descent) as well as holding patterns at various altitudes. It uses this information to allow air to escape continuously from the airplane by further opening or closing the outflow valve. Thus, the cabin internal pressure is controlled by modulating the exhaust airflow through the escape valve (outflow valve). As the airplane changes altitude, the outflow valve repositions itself to allow more or less air to escape. While the external ambient pressure is equivalent to the altitude of 36,000 ft, the cabin pressure is maintained at approximately 8,000 ft due to the physiological human requirements (mainly the respiratory needs). This leads a high differential pressure between the cabin and the external environment implying in more intense structural efforts to the fuselage. The outflow valve is constantly being positioned to maintain cabin pressure as close to sea level as practical, without exceeding a predetermined cabin-to-outside pressure differential. In this context, this work focuses on the determination of the outflow valve opening area of the aircraft cabin pressurization system for ground and flight schedules, considering: (i) the inflow supplied by the air-conditioning packs; (ii) cabin leakages and (iii) the pressure change rate. The cabin leakage is modelled using the orifice compressible flow theory and the inflow rate is constant (determined by the cabin ventilation requirements). Results are obtained using a typical aircraft flight mission (schedule).*

Keywords*: Pressure control system, outflow valve, ACM, leakage airflow, cabin pressure differential*

1. Introduction

Based upon the operational parameters of the aircraft and the length of the trip, it is desirable to fly at the highest practical altitude. From an economical perspective, at a given airspeed, turbine engine fuel consumption decreases as altitude increases (Lombardo, 1993). Being able to select a higher altitude may give you the option of a smoother ride, shorten your flying time, and/or provide an alternative to flying in severe weather or icing conditions. A pressurized aircraft can provide a comfortable cabin environment at significantly higher altitudes than one that is unpressurized, in which the passengers are required to wear oxygen masks. Today there are a number of aircraft that feature pressurization systems that result in shorter flight times, lower fuel burns, higher endurance, and weather avoidance.

Cabin pressure is controlled modulating the cabin exhaust airflow. Because there is also a permanent leakage flow of air out of the cabin through cracks, doors, window assemblies, and other points, it is necessary to ‘pump in’ more air than the controlled exhaust airflow rate used to adjust the desired cabin pressure by regulating the outflow valve opening. The constant input airflow supplied by the air-conditioning machine (ACM) must be sufficiently high to keep the cabin airflow fresh.

An aircraft pressurization system has three primary goals: a) maintain a maximum cabin pressure altitude of approximately 8,000 ft at the aircraft maximum designed cruise altitude; b) prevent unwanted, rapid changes of cabin altitude regardless of rate of climb or descent and c) reasonably fast fresh air exchange to eliminate odors and remove stale air.

There are three types of cabin pressurization control system (CPCS): fixed-isobaric, variable-isobaric and isobaric-differential. The fixed isobaric system always sets the cruise cabin pressure to the same fixed value. The cruise cabin pressure can be set to an adjustable value in the variable isobaric system. The isobaric-differential CPCS adjusts the pressure cabin to a constant value when the aircraft altitude is in the range between 8,000 ft and 23,000 ft. From 23,000 ft until the permissible aircraft maximum altitude, the cabin altitude varies due to limitations in structural strength.

A typical CPCS consists of primary valves (outflow valves) and secondary safety valves (Lombardo, 1998). The primary valve is utilized to maintain a given cabin altitude, typically 8,000 ft. The safety valve, independent of the primary, was set to open under any one of three conditions: when the cabin experienced maximum delta pressure, negative delta pressure, or when the aircraft was sitting on the ground.

The maximum pressure differential value varies from aircraft to aircraft, depending on system and structural limitations and the type of operation for which the aircraft is designed. Another factor that determines the maximum possible cabin pressure is the type of pressurization system used.

Passenger comfort requires that the system have adequate response to handle the transients that result from take-off rotation, engine power change, adding or subtracting a cooling pack and engine bleed stage switchover operation (SAE, 2000).

All cabin pressurization systems incorporate an outflow valve or valves (SAE, 2000) which regulate the cabin overboard flow rate (the cabin inflow air rate minus leakage) to control the pressure inside the cabin, as schematized in Fig. 1.

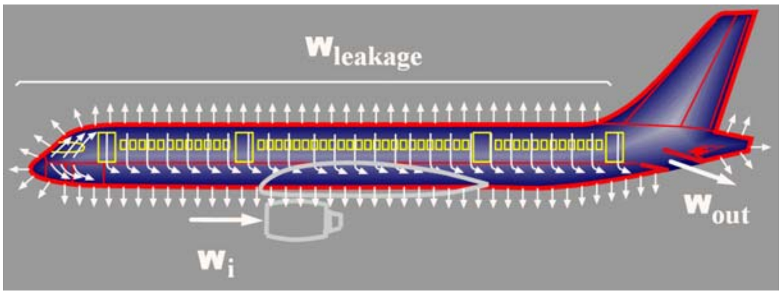


Figure 1 Schematic representation of the cabin mass balance parcels.

Assuming isothermal conditions, the time for the pressure to equalize depends on the cabin volume, the effective area of the outflow valve, the cabin inflow, and the pressures inside and outside the cabin. If the size of the effective area of the valve is small in comparison to the cabin volume, the rate of pressure change may be too slow to equalize the pressures before an adverse event could occur.

The flow of air through an outflow valve is determined by the degree of valve opening. This valve is ordinarily controlled by an automatic system which can be set by the flight crewmembers. A few simple minor adjustments are required on the average flight, but most of the time automatic controls need only to be monitored. In the event of a malfunction of the automatic controls, manual controls are also provided.

2. Mathematical formulation

In this work presents a computation methodology established by a lumped parameters approach to determine the outflow valve opening area for typical aircraft flight. The aircraft pressurization system can be mathematically modeled applying a mass balance, Figure 1, involving the input and output airflows into and from the cabin control volume. The time rate of the accumulated mass inside the cabin can be expressed by:

$$\frac{dm}{dt} = W_i - W_{out} - W_{leakage} \tag{1}$$

where:

$\frac{dm}{dt}$	cabin accumulated air mass
W_i	airflow supplied by the ACM (Air Conditioning Machine)
W_{out}	airflow leaving the cabin through the outflow valve
$W_{leakage}$	fuselage airflow leakage

The mathematical model represents the analytical form of the physical phenomenon involved in this problem. The air inflow supplied by the ACM (Air Conditioning Machine) is determined by the imposed fresh airflow certifications requirements, Hunt and Space (1994), of 5 liters/minute per occupant.

The cabin air is assumed to obey the perfect gas equation:

$$pV = \frac{m}{M} RT = mR_{air}T \tag{2}$$

where:

p	pressure
V	volume
m	airflow mass
M	air molecular mass
R	universal gas constant
T	temperature
R_{air}	air gas constant
t	time

Substituting Eq. (2) in Eq. (1) results:

$$\left(\frac{V}{R_{ar}T}\right)\frac{dp}{dt} = W_i - W_{out} - W_{leakage} \tag{3}$$

The hydrostatic relationship applied at sea level results in the following equation:

$$\frac{dp}{dh} = -\rho g \tag{4}$$

where:

h	altitude
ρ	density
g	gravity acceleration

When Eq. (1) is written in the form:

$$W_{out} = W_i - W_{leakage} + \left(\frac{\rho_c g V_c}{R_{ar}T_c}\right)\left(\frac{dh}{dt}\right)_c \tag{5}$$

where c subscript refers to the aircraft cabin.

The cabin leakage has a controlled parcel represented by the toilet exhaust, electronic compartment ventilation and other control vents. The magnitude of the uncontrolled cabin leakage must be kept low enough to provide a minimum finite airflow at all times through the outflow valve for pressure regulation purposes (SAE, 2000).

Considering compressible airflow through orifice (SAE, 2000), the cabin air mass leakage is determined by:

$$W_{leakage} = CA\sqrt{2\frac{\gamma}{\gamma-1}\rho_c p_c Z} \tag{6}$$

where:

C	flow coefficient
A	equivalent area

where Z is defined as:

$$Z = (rp)^{\frac{2}{\gamma}} - (rp)^{\frac{\gamma+1}{\gamma}} \quad \text{for } 0.53 \le rp \le 1 \tag{7}$$

$$Z = 0.256 \quad \text{for } rp < 0.53 \tag{8}$$

where:

$rp = \frac{p_a}{p_c}$	pressure ratio
p_a	atmospheric (external) pressure
p_c	cabin pressure
$\gamma = \frac{c_p}{c_v}$	rate of the specific heats
c_p	constant pressure specific heat
c_v	constant volume specific heat

The International Standard Atmosphere (ISA) pressure was calculated by Eq. (9):

$$p_a(z) = 101325\left(1 - 2.25577 \cdot 10^{-5} \cdot z\right)^{5.2559} \quad (9)$$

To obtain the aircraft flight pressure schedule the exhaust airflow through the outflow valve is calculated by Eq. (5). To attain this exhaust airflow through the outflow valve, the opening area of the valve must be modulated. Considering compressible airflow through outflow valve Eq. (10) is obtained to determine the opening area:

$$A = \frac{W_i - W_{leakage} + \left(\frac{\rho_c g V_c}{R_{ar} T_c}\right)\left(\frac{dh}{dt}\right)_c}{C\sqrt{2\frac{\gamma}{\gamma - 1}\rho_c p_c Z}} \quad (10)$$

3. Results

The mathematical model equations simulating the aircraft cabin pressurization system were implemented in the Mathcad® software, Mathsoft (1999), with the parameters defined in Table 1.

Table 1 – Parameters definition used in the numerical simulations

Cabin volume	Vc = 500 m^3
Cabin temperature	Tc = 25^{o}C
Cabin air mean density	ρ = 1.1774kg/m^3
Occupants number	N = 60
Flow coefficient	C = 1

The aircraft and cabin altitude must have the profiles shown in Fig. 2. The cabin altitude profile presented in Fig. 2 means that absolute internal pressure is equal to the ISA (International Standard Atmosphere) pressure at the altitude shown (pressure unit used in this work is the ISA altitude). Aircraft and cabin exhibit a climb, cruise and descent flight stages. Figure 3 presents a zoom view of the altitude profiles showing the ground pre-pressurization procedure before aircraft takeoff and the depressurization after landing.

Between aircraft takeoff and landing the aircraft and cabin exhibit a climb, cruise and descent flight stages Fig. 2. The cabin pressure increases slightly when the door is closed and air-conditioning input air flow passes through outflow valve (Fig. 3.a). Next, in order to avoid the takeoff pressure bump, the cabin is pre-pressurized to -350 ft (106.68 m), at a descent rate of -450 ft/min (-2.28 m/s). After aircraft takeoff, the cabin altitude must increases at a climb rate of 2.5 m/s until 8,000 ft is reached (cabin cruise altitude).

When the aircraft descent begins, the cabin altitude decreases at a descent rate of -1.5 m/s (Fig. 2). In order to avoid the landing pressure bump, the cabin is over-pressurized to an altitude of -300 ft relative to landing airport (Fig. 3.b). The cabin must be depressurized before the aircraft door opening at a rate of -3.3 m/s.

Table 2 presents the flight time definitions for the scheduled mission shown in the Figure 2. The cruise time-interval was intentionally reduced to allow the enlargement of the other flight stages.

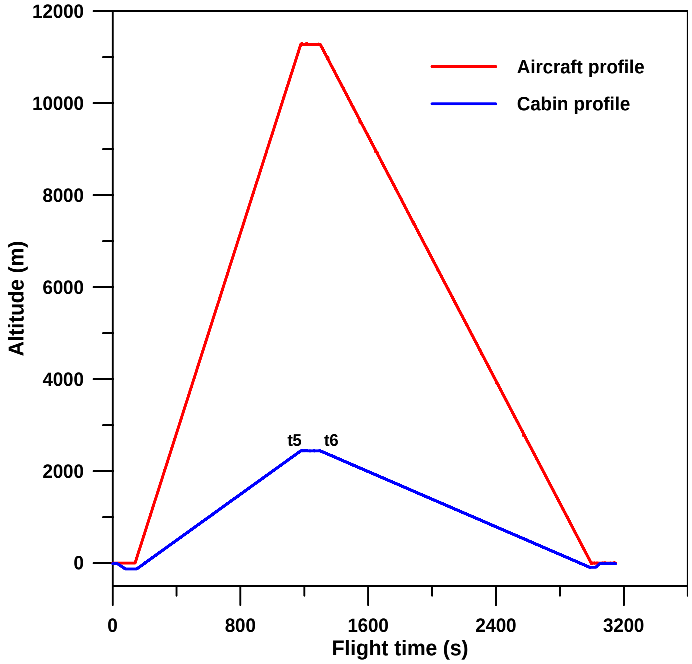
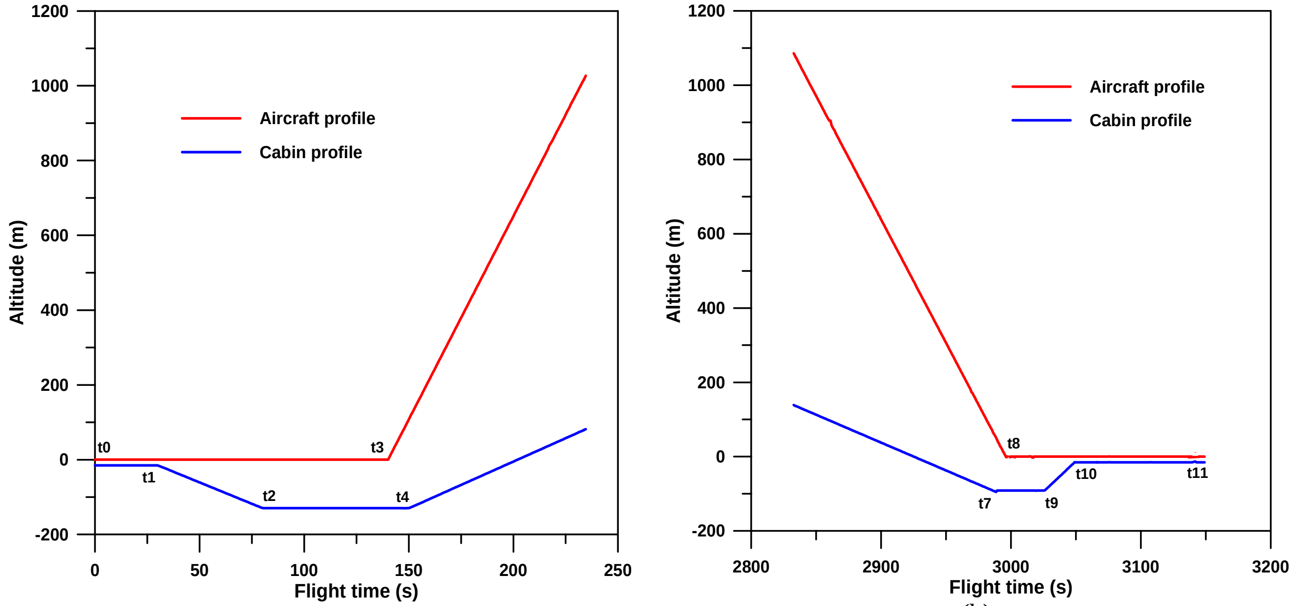


Figure 2 – Aircraft and cabin altitude profiles.



(a) (b)

Figure 3 – Zoom view of the Figure 1: (a) initial flight time and (b) final flight time.

Table 2 – Time definitions for the profile shown in Figure 2

t0= 0s	Initial time
t1 = 35s	Ground cabin pre-pressurization initial time
t2 = 80.1s	Ground cabin pre-pressurization final time
t3 = 140.1s	Aircraft takeoff time
t4 = 150.1s	Cabin altitude climb initial time
t5 = 1177.4s	Cruise altitude initial time (cabin and aircraft)
t6 = 1299.4s	Descent altitude initial time (cabin and aircraft)
t7 = 2986s	Time that the landing cabin pressurization finishes
t8 = 2996s	Aircraft landing time
t9 = 3026s	Time that the cabin altitude depressurization begins, after the aircraft landing
t10 = 3049s	Time that the cabin altitude is equal to -50 ft.
t11 = 3149s	Time that the ACM (Air Cycle machine) is turned-off.

Figure 4 and Figure 5 show the outflow valve opening area, the fuselage leakage airflow variations and cabin pressure differential during the flight time. Figure 6.a and Figure 6.b depict zoom views of the initial and final stages of the aircraft total mission, respectively.

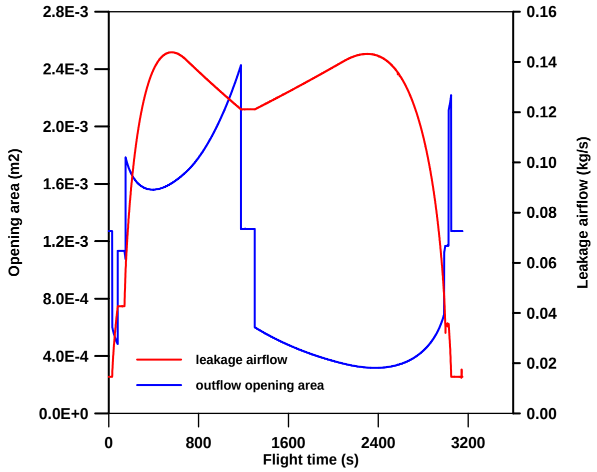


Figure 4 – Outflow valve opening area and cabin leakage airflow.

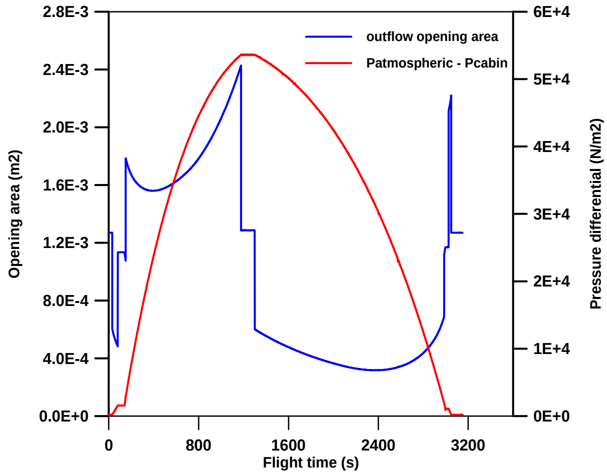
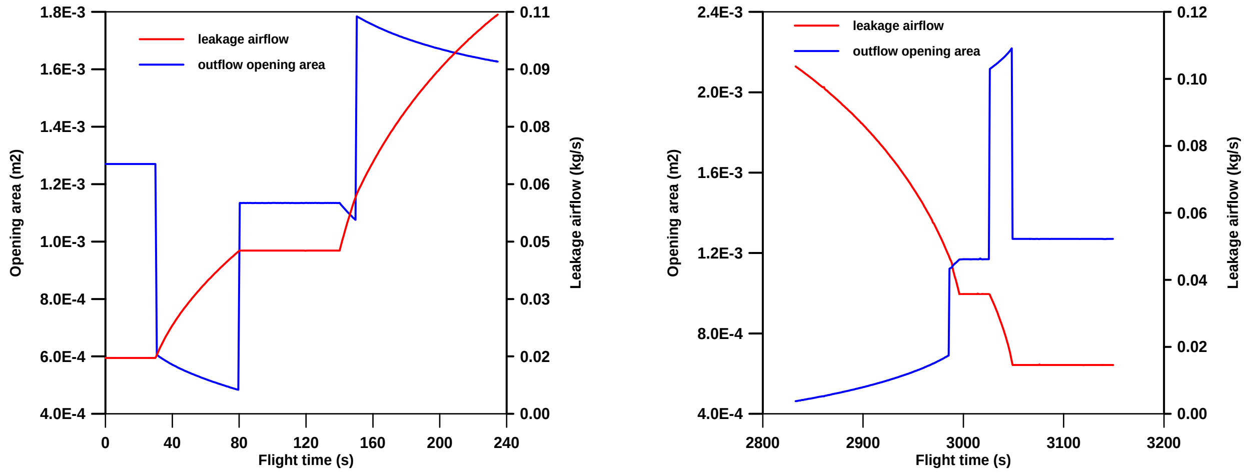


Figure 5 – Outflow valve opening area and pressure differential between atmospheric/cabin pressure.



(a) (b)

Figure 6 – Zoom view of the Figure 4 (a) initial flight time and (b) final flight time.

For the $t0 \le t \le t1$ time-interval (Fig. 3.a), the aircraft doors are closed, the cabin pressure is constant, as is the valve opening area (internal air mass constant) and the cabin pressure differential is also constant (leakage airflow is constant). So, the airflow through the outflow valve is constant and its opening area (Fig. 6.a).

At $t1$ time instant, the outflow valve abruptly reduces its opening area to decrease the overboard air flow and obtain cabin ground pre-pressurization. This procedure reduces the effects of the takeoff pressure bump.

For the $t1 \le t \le t2$ time-interval (Fig. 3.a), the outflow valve progressively closes (Fig. 6.a) to compensate the increases in leakage air flow (Fig. 6.a) due to the elevation of the cabin pressure differential.

At $t2$ time instant, the cabin pressure reaches the -350 ft (106.68 m) altitude level and the outflow valve rapidly increases its opening area to be maintained constant during the $t2 \le t \le t3$ time-interval.

The aircraft takeoff occurs at the instant $t3$, thus the cabin pressure differential increases (Fig. 6.a). As a consequence, the leakage airflow also increases. Therefore, to maintain the cabin altitude constant (Fig. 3.a), the outflow valve opening area is progressively reduced during the $t3 \le t \le t4$ time-interval.

When the cabin altitude begins to increase ($t4$, Fig. 3.a) due to the required reduction rate of the cabin air mass, Fig. 6.a, the outflow valve should be quickly opened.

For the $t4 \le t \le t5$ time-interval, the outflow opening area varies to compensate the leakage mass airflow that changes as a function of the cabin pressure differential. Before the pressure ratio reaches its critical value, the leakage airflow increases, Fig. 4. After this critical point, the leakage airflow decreases because the cabin air density decays.

At $t5$, the aircraft and the cabin altitude reaches their cruise levels and the cabin air mass stabilizes causes an abrupt reduction of the outflow valve opening area, Fig. 2. At the cruise stage, the pressure (air mass) and the pressure differential (leakage airflow) of the aircraft cabin are maintained constant. Thus, the outflow valve opening area is constant.

At the start of the descent flight stage the outflow valve should be partially closed to reduce air flow from cabin and increase the accumulated air mass. For the $t6 \le t \le t7$ time-interval, the outflow opening area varies to compensate the leakage outflow and maintain a constant increase rate of cabin air mass, Fig. 4.

The landing over-pressurization level of -300 ft is attained in the $t7$ time instant and the cabin pressure should be maintained constant, Fig. 3.b. Therefore, the outflow valve should be partially open to increase the overboard airflow, Fig. 6.b. For the $t7 \le t \le t8$ time-interval, the cabin pressure differential is decreasing and the outflow valve opening area should be progressively increased.

The aircraft landing occurs at $t8$ time instant, Fig. 3.b. For the $t8 \le t \le t9$ time-interval, the pressure differential and the cabin pressure are constants; hence the outflow opening area should be constant, Fig. 6.b.

The cabin depressurization in the airport landing begins at $t9$, hence the outflow valve should be abruptly opened. For the $t9 \le t \le t10$ time-interval, the pressure differential and cabin pressure are reducing at time rate of -3.3 m/s, Fig. 6.b. To maintain a constant air outflow the opening area should be progressively increased. At $t10$ time, the cabin pressure reaches the -50 ft level, Fig. 6.b, therefore the outflow valve opening area can be reduced to a constant value in the $t10 \le t \le t11$ time-interval.

The aircraft door can be opened after $t11$ time instant, Fig. 6.b.

4. Conclusions

In this work, the cabin pressurization was numerically simulated and the necessary outflow valve opening area was calculated to obtain both the cabin pressure flight profile and the aircraft passenger comfort and safety conditions. The pressurization system dynamic was not taken in account. Therefore, the results of the present work must be used only to determine the maximum required outflow valve opening area.

5. Acknowledgements

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