Civil Aircraft Cabin Pressure System Decompression Calculation and Analysis

Zheng Bian [1, a]

[1] Shanghai Aircraft Design and Research Institute, Commercial Aircraft Corporation of China Ltd., Shanghai, China

[a] bianzheng@comac.cc

Abstract. This paper presents a comprehensive analysis of decompression scenarios in civil aircraft cabin pressure systems, focusing on calculation methodologies and safety assessments. The study addresses potential risks arising from structural breaches, pressure regulation failures, and supply system malfunctions, which could lead to hazardous cabin altitude increases. By employing orifice flow theory and dynamic valve adjustment models, the research calculates critical leakage areas under various conditions, including different PACK air supply statuses and cabin altitude warning scenarios. The results demonstrate compliance with airworthiness regulations such as CCAR 25.841, ensuring that cabin altitude thresholds (e.g., 15,000 feet) are not exceeded during system failures. The findings provide essential insights for optimizing emergency descent strategies, enhancing structural redundancy, and supporting airworthiness certification processes.

Keywords: Civil aircraft, Cabin pressure system, Decompression analysis.

1. Introduction

During high-altitude flight, the external atmospheric pressure of an aircraft is significantly lower than that at ground level. If the cabin pressure cannot be maintained within a reasonable range, it poses a serious threat to the safety of passengers and crew. Therefore, modern civil aircraft are universally equipped with cabin pressurization systems to simulate a ground-like atmospheric environment. However, decompression risks caused by system failures, structural damage, or emergencies (e.g., explosions, impacts) still exist. Without thorough analysis and design, such risks may lead to catastrophic consequences.

Decompression incidents in the cabin can occur due to various failure scenarios, including air conditioning system malfunctions, structural breaches, or pressure regulation system failures. A notable example in aviation history is the Helios Airways Flight 522 disaster, a tragic accident caused by prolonged decompression.

The causes of cabin pressure loss or anomalies can be summarized as follows:

a) Structural issues, such as skin ruptures, cracks in specific areas, or non-contained rotor bursts and windshield failures identified in hazard analyses;

b) Pressure regulation system failures, primarily due to faults in pressure controllers, pressure relief valves, or pressure sensors, with pressure controller failures being the most frequent;

c) Supply system failures, including leaks in upstream bleed air systems or air conditioning systems, flow control valve malfunctions, or insufficient bleed air volume.

The core objective of decompression analysis is to predict, assess, and quantify potential cabin pressure loss scenarios during the aircraft design phase[5]. This enables the development of reasonable structural redundancy plans, safety warning thresholds, and emergency response strategies. By analyzing critical leakage areas under typical conditions—such as warning states, air supply statuses, and environmental altitudes—the fault tolerance boundaries of the system design can be clarified, providing key references for structural design, safety evaluations, and airworthiness reviews.

In practical applications, decompression analysis is not only a prerequisite for complying with airworthiness regulations like CCAR 25.841 and FAR/JAR 25.831 but also the foundation for achieving "safe, controllable, and emergency-feasible" pressurization systems. Specific application scenarios include:

a) Safety compliance verification during airworthiness certification;
b) Optimization of emergency descent strategies in flight envelope design;
c) Adaptation of airtightness designs for high-altitude airport operations;
d) Inputs for fault tree analysis (FTA) and failure mode and effects analysis (FMEA) of the pressurization system[3];
e) Support for overall airframe structural strength and pressure resistance evaluations.

This paper focuses on decompression calculation and analysis for internal failure scenarios in civil aircraft cabin pressurization systems.

2. Decompression Calculation and Analysis for Civil Aircraft Pressurization Systems

2.1 Calculation Methodology

This section outlines the overall calculation method for cabin decompression analysis in civil aircraft. The core task is to determine the critical leakage area (or allowable breach area) corresponding to specific cabin altitude thresholds under different operating conditions (with/without cabin altitude warnings, with/without PACK air supply)[1].

For critical cabin altitude values, the requirements of CCAR 25.841 are primarily considered:

Pressurized cabins and compartments carrying occupants must be equipped with systems to ensure that, under normal operating conditions, the cabin pressure altitude does not exceed 2,438 meters (8,000 feet) at the maximum operating altitude.

a) If certification for operations above 7,620 meters (25,000 feet) is sought, the aircraft must be designed so that occupants are not exposed to a cabin pressure altitude exceeding 4,572 meters (15,000 feet) after any possible pressurization system failure.
b) The aircraft must be designed so that any failure not demonstrated to be extremely improbable does not expose occupants to a cabin pressure altitude exceeding:
    i. 7,620 meters (25,000 feet) for more than 2 minutes; or
    ii. 12,192 meters (40,000 feet) for any duration.

Different calculation methods are used for scenarios with and without cabin altitude warnings.

2.1.1 For scenarios with cabin altitude warnings

When the cabin altitude reaches 10,000 feet, a warning is issued. Accounting for system response time, the aircraft begins an emergency descent after a specified delay (X seconds)[4]. The critical geometric leakage area for the cabin altitude exceeding *h* feet is then calculated. The steps include:

a) Building the orifice flow model as the main calculation module.
b) Setting calculation inputs: emergency descent envelope, flow rates, cabin temperature, initial cabin and ambient pressures, cabin airtight zone volume, and equivalent leakage area.
c) Constructing logic modules for "warning at 10,000 feet," "emergency descent after X seconds," and "cabin altitude exceeding *h* feet."
d) Using the cabin altitude *h* to define a function and iteratively solve for the critical leakage area via the bisection method, with an error limit of 10^-7[6].

2.1.2 For scenarios without cabin altitude warnings

The aircraft’s service ceiling cruise altitude is used to calculate the critical leakage area corresponding to the cabin altitude rising to *h* feet. The steps include:

a) Building the orifice flow model as the main calculation module.
b) Setting inputs: service ceiling altitude (39,500 feet), flow rates, cabin temperature, initial pressures, cabin volume, and equivalent leakage area.
c) Omitting the warning and emergency descent modules.

d) Iteratively solving for the critical leakage area via the bisection method, with an error limit of 10^-7.

For both scenarios, the core workflow includes input modules (cabin volume, leakage area, temperature, pressure), calculation modules (based on orifice flow theory), warning modules (if applicable), and output display modules. The simulation constructs a target function for "cabin altitude = *h*" and uses numerical iteration to derive the critical leakage area, providing data for safety assessments.

2.2 Calculation Inputs and Assumptions

Inputs for decompression calculations in civil aircraft cabin pressure systems include:

a) The aircraft's fastest emergency descent envelope (for warning scenarios);
b) Fresh air flow rates, including single and dual PACK supply flows;
c) Cabin airtight zone volume;
d) Equivalent leakage area for the entire aircraft;
e) Cabin temperature;
f) Initial cabin and ambient pressures.

Additional assumptions:

a) The aircraft is treated as a single airtight compartment.
b) After a breach occurs, the outflow valve closes linearly and completely.

2.3 Main Calculation Modules

2.3.1 Orifice Flow Calculation Module

The basic orifice flow formulas used in aircraft cabin pressure systems are as follows[2]:

a) Subcritical flow model (Equation 1):

When $P_a / P_c \geq 0.5283$,

$$Q=\frac{CA\times 0.156P_c\sqrt{\left(\frac{P_a}{P_c}\right)^{1.43}-\left(\frac{P_a}{P_c}\right)^{1.71}}}{\sqrt{T}\times\rho} \qquad (1)$$

b) Supercritical flow model (Equation 2):

When $P_a / P_c < 0.5283$,

$$Q=\frac{CA\times P_c}{24.77\times\sqrt{T}\times\rho} \qquad (2)$$

c) Air density is calculated using the ideal gas law (Equation 3):

$$\rho=\frac{P_c}{R\times T} \qquad (3)$$

Where:

Q: Cabin air supply rate (m³/s);
CA: Effective exhaust area (m²);
Pc: Cabin pressure (Pa);
Pa: Ambient pressure (Pa);
T: Cabin air temperature (K);
ρ : Cabin air density (kg/m³);
R: Gas constant for air (287 J/(kg·K)).

The orifice flow calculation module is illustrated in Figure 1.

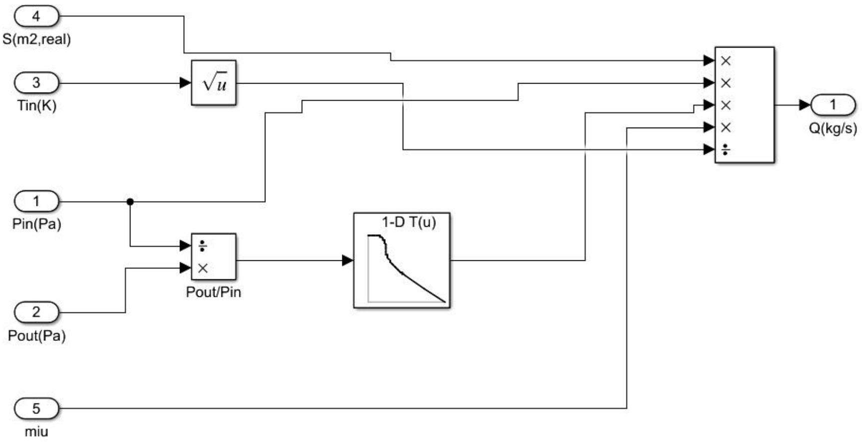

Fig. 1: Orifice Flow Calculation Module

(Inputs: breach area, cabin temperature, internal/external pressures; Output: flow rate for the given breach area.)

2.3.2 Outflow Valve (OFV) Opening Area Calculation Module

The OFV's opening area directly affects the rate of air expulsion from the cabin, influencing pressure changes. To accurately simulate decompression, the effective exhaust area must be calculated in real time based on valve opening angles.

The module's logic:

a) Inputs: Valve opening (angle or percentage), geometric parameters (e.g., diameter, structural coefficients).
b) Geometric approximation for the opening area (e.g., for a circular valve: $A=\pi r^2 \cdot \theta/\max\theta$)).
c) A correction factor η accounts for structural irregularities.
d) Output: Time-varying effective opening area, used as input for the orifice flow model.

The module supports dynamic feedback (e.g., "pressure exceeds limit → valve opens further → pressure drops") and can be configured for different valve types or fault simulations (e.g., jamming, lag).

The OFV opening area module is shown in Figure 2.

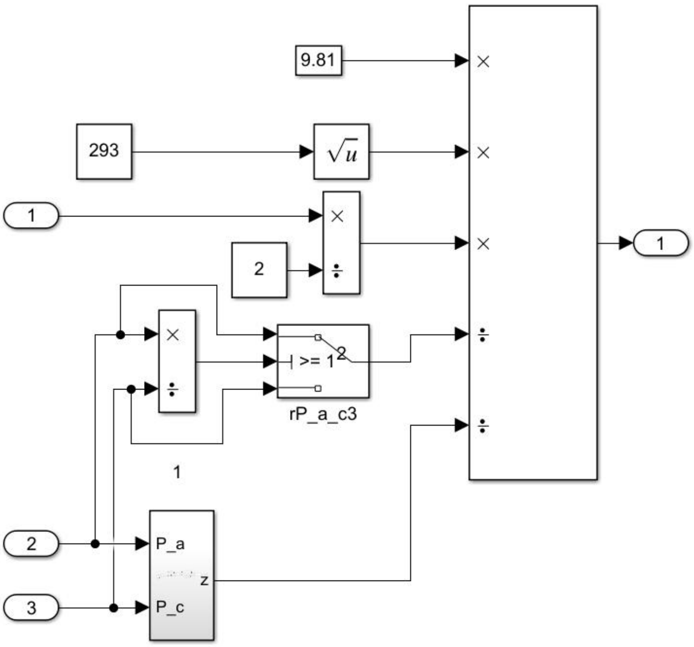

Fig. 2: OFV Opening Area Calculation Module

Other modules (e.g., input setup, warning logic, display) are omitted here for brevity.

2.4 Calculation Results

The model yields decompression results for the cabin pressure system, as shown in Table 1.

Table 1. Calculation Results

No.	Cabin Altitude Warning	PACK Status	Critical Cabin Altitude (ft)	Critical Effective Flow Area (cm²)
1.	Y	2P	10,000	182.3
2.			15,000	398.2
3.			25,000	891.7
4.		1P	10,000	87.0
5.			15,000	215.2
6.			25,000	703.3
7.		0P	10,000	0
8.			15,000	21.6
9.			25,000	398.1
10.	N	2P	10,000	178.9
11.			15,000	234.1
12.			25,000	435.6
13.		1P	10,000	86.8
14.			15,000	116.6
15.			25,000	208.3
16.		0P	10,000	0
17.			15,000	0
18.			25,000	0

Notes:
2P: Dual PACK operation (normal air supply)
1P: Single PACK operation (reduced air supply)
0P: No PACK operation (loss of air supply)
Y/N: Indicates whether a cabin altitude warning is triggered (Yes/No).

Explanations:

a) Values represent the maximum allowable breach area (cm²) before cabin altitude exceeds the specified threshold.
b) A "0" indicates no safe breach area exists under the given conditions (immediate decompression risk).

2.5 Analysis of Decompression Results for System Failure Scenarios

The model calculates critical breach areas compliant with CCAR 25.841(a)(2)(i). Comparing these with system failure scenarios (e.g., valve stuck open at 400 cm²) leads to the following conclusions:

a) Dual PACK operation: Maximum breach area (400 cm² + 30 cm² leakage) = 430 cm², below the critical 891.7 cm².
b) Single PACK operation: 430 cm² < 703.3 cm² (critical).
c) Dual PACK failure: 400 cm² exceeds the critical area, but the combined failure probability is <1E-9/FH (extremely improbable).

Thus, except for extremely improbable combinations, the system meets CCAR 25.841(a)(2)(i) requirements.

3. Summary

This paper analyzes the response mechanisms and safety margins of civil aircraft cabin pressure systems under decompression scenarios, based on design requirements and airworthiness standards. By studying control logic, system architecture, and decompression triggers, a simulation model incorporating orifice flow theory and dynamic valve adjustments was developed.

The parametric framework adapts to various scenarios (e.g., warning states, PACK configurations), using iterative methods to derive critical leakage areas. The results provide reliable safety boundaries for aircraft design.

In conclusion, this research offers practical value in model construction, simulation design, and data analysis. It directly supports decompression protection design and engineering validation for civil aircraft, enhancing overall safety and operational risk reduction.

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