Research Article

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Analysis of electrostatic filter to mitigate ash diffusion into engine

Abstract

Between March and June 2010 a series of volcanic events at Eyjafjallajökull in Iceland caused enormous disruption to air travel across Western Europe. The disruptions started over an initial period of six days in April 2010. About 20 countries closed their airspace to commercial jet traffic and it affected approximately 10 million travelers. Volcanic ash has been caused grounding of many aircraft as a source of possible damage to aircraft engines. The projected technical strategy, an electrostatic precipitator (ESP), was tailored for the high bypass turbofan engine model PW4000 in this study. It was based on the standard two-stage ESP but designed with the PW4000 engine. The innovative ESP prototype is primarily made up of a hexagram structure of six discharge electrode plates and three circular collecting electrode rings.

An aerodynamic verification was conducted through computational fluid design (CFD). It built a 20-meter wind tunnel and placed the engine with ESP in the centre of it. A particle-laden atmosphere was created in the simulation using a discrete phase model (DPM) to replicate volcanic ash injection into clean air. From the results, it has a clear aerodynamic impact near the engine's intake, although the effect is small and may be ignored after the engine fans. Additionally, a CFD electrostatic verification was generated with a voltage of 20000 V, and the contour of the electric potential is perfect distributed, suggesting that an electric field can be adequately given by this ESP configuration design. Therefore, the simulation results of the new ESP layout would have allowed drawing conclusions about the electrostatic filter's ability to reduce volcanic ash intake in an engine with high aerodynamic performance.

Keywords: electrostatic filter, engine, aerodynamic, computational fluid design

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Introduction

The eruption of Iceland's Eyjafjallajökull volcano in March 2010, which lasted until the end of May, led in the longest and greatest shutdown of European aviation since World War II. This airspace closure has both human and economic ramifications. Millions of passengers were affected each day, with a total loss of 1.1 billion pounds anticipated. The main reason is that volcanic ash poses a significant risk to aircraft. The plane suffers from one of the most damaging engine flaws in two ways: corrosion of the fans and blades and blockage of the fuel nozzles. As a result, engine running time is reduced in particle-laden environments, and the engine may sustain irreparable damage.[1-14]

One proposed technological method is the electrostatic precipitator (ESP). It is a particle control device that uses electrical forces to remove tiny particles. It may suit the demands of the turbofan engine to decrease volcanic ash during operation. The aerodynamic impact of in-flight ESP may be minimised with careful design. The two-stage precipitator invented by Penney is a series device with the discharge electrode, or ionizer, preceding the collector electrodes. This arrangement has the advantages of increased time for particle charging, reduced proclivity for back corona, and cost-effective fabrication for small quantities. The vivo ESP will be based on a two-stage arrangement in this study, giving the commercial high-bypass turbofan engine a chance to install an ESP in and filter volcanic ash as needed.

This paper will evaluate the in-vivo ESP design from the aerodynamics and electric field perspectives using computational fluid design (CFD). In the evaluation, a typical commercial turbofan engine type PW4000 will be used. The results are intended to indicate that the new ESP geometry's aerodynamic influence may be ignored during cruising and that the electric potential distribution is optimum under the novel ESP geometry design. As a result, it may present the possibility of applying this novel ESP notion in future study.

Protype of a vivo ESP

Operating process of a two-stage ESP

An electrostatic filter removes microscopic particles through three steps. To begin, a negative electric field (created by a discharge electrode) is utilised to ionise the volcanic ash. The most practical approach to ionise air molecules is to create a corona discharge. A negative electric field is initially formed between the discharge electrodes. When the voltage applied is adequate, the neutral gas molecules that travel through the electric field are ionised. After releasing one electron, they change into cations. The positively charged gas molecules collide with the liberated and unbound electrons. Each impact generated a new electron. As a result, electrons are moving about in this region, and the negative electric field repels them, causing them to accelerate and occupy a greater space. Subsequently, the charged molecules and ions will cling to the dusts' surfaces (ash). Following that, the charged particles are drawn to collecting surfaces that have the opposite charge. Finally, the gathered particles are removed or rejected by the rapping system.

Two-stage ESP is one of the vivo forms (Figure 1). The benefits of a two-stage arrangement include longer time for particle charging, a lower proclivity for back corona, and cost-effective construction for small quantities. This sort of precipitator is commonly employed for gas flow sub micrometric sources such as smokes or other sticky particles, such as diesel exhaust cleaning and interior air cleaning in homes, hospitals, and food plants. However, there are no references to its application in aircraft engine arrangement or in the ECS.

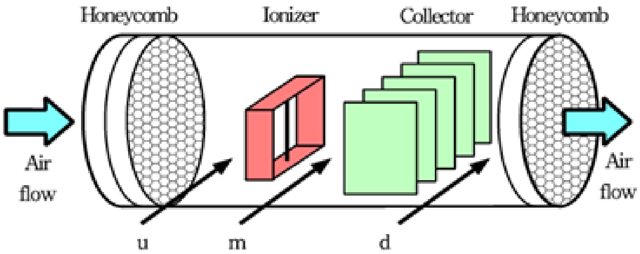

Figure 1 The configuration of two-stage ESP.

Turbofan engine

Turbofan engine is the most modern variation of the basic gas turbine engine. In the turbofan engine, the core engine is surrounded by a fan in the front and an additional turbine at the rear. The fan and fan turbine are composed of many blades, like the core compressor and core turbine, and are connected to an additional shaft. As with the core compressor and turbine, some of the fan blades turn with the shaft and some blades remain stationary. The fan shaft passes through the core shaft for mechanical reasons. This type of arrangement is called a two spool engine (one "spool" for the fan, one "spool" for the core.) Some advanced engines have additional spools for even higher efficiency. Here the forward-fan high and ultrahigh bypass turbofan engine function is studied, which is often employed in modern civil aviation aircraft engines. Model PW4000 is a common and effective engine family for it. Model PW4000 was utilised to approximate the basic engine size and internal surface area that may be used for electrodes (Figure 2 & Table 1).

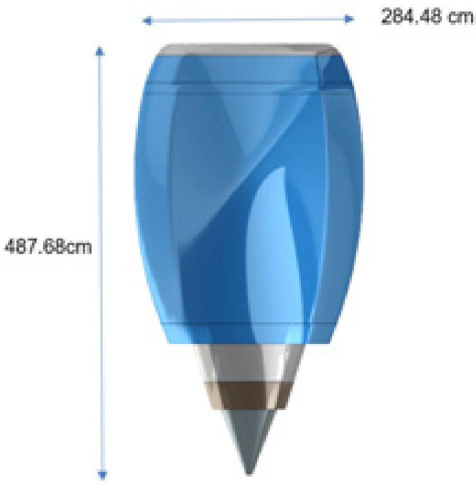

Figure 2 The general dimension of engine PW4000.

Table 1 The estimated turbofan engine area for ESP

Parameters	Magnitude
Total area of ESP discharge electrodes	14.225 m^2
Total area of ESP collection electrodes	9.5 m^2

The vivo ESP prototype

Figure 3 depicts the whole concept of the new ESP; the blue sections are the discharge electrodes and orange sections are the collection ones.

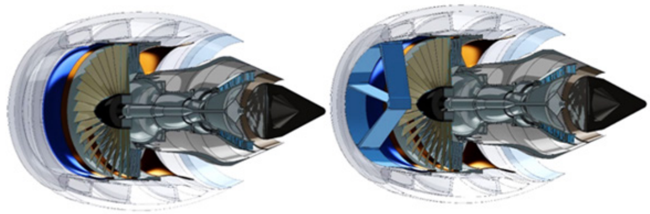

Figure 3 The novel ESP design.

For the first idea, according to the initial electrodes area estimation (10 m^2), the "first stage" component, discharged electrode portion, is built as a "thin hexagram" (6 plates) arranged in a cylinder to fulfil the area requirement. The present "hexagram" component is detachable. As a result, the impact (aerodynamic and mass) of the permanent element (the outer cylinder) may be practically disregarded during routine daily flying. The "second-stage" collecting electrodes are divided into three portions (the orange "rings") (also estimated under the collection electrodes area demand). During production, all portions of the collecting electrodes will be attached to the inside surface of the nacelle. The thickness of the electrode should be kept to a minimum. The first ring is in front of the engine fan, the second is between the fan and the core engine's intake and the last one is near to the nacelle's outlet, improving the ESP's gathering potential. All the rings' edges were given flat fillets or champers to reduce the aerodynamic influence on engine efficiency.

Mass analysis of the vivo ESP

Because the majority of the ESP components are mounted in the engine, the bulk of the ESP should be kept to a minimum, avoiding effect for 99.9% of routine everyday flights. A PW4000-94 engine weighs 4273 kg, a PW4000-5851 engine weighs 5851 kg, and a PW4000-112 engine weighs 7375 kg. The mass calculations of the ESP for different electrode plate thicknesses under normal (clear air) and atypical (flights through the volcanic ash cloud) conditions are listed in Table. The ESP is made of stainless steel in this case. Equation 1 is used to compute the mass gain percentage for the engine.

$$\textit{Mass Increse Percentage} = \frac{\textit{ESP Load Mass}}{\textit{Engine Mass} + \textit{ESP Load Mass}} \tag{1}$$

According to Table 2, the maximum mass gain for one engine in normal flight is 13.3 kg with built-in ESP components and 23.3 kg in exceptional flight with complete ESP. Both weights are less than a passenger's baggage weight restriction (usually 25 kg). As a result, it is fair to disregard the ESP's mass influence during flight.

Results and discussion

The aerodynamic results show that air density increases in front of the engine and shortly returns to normal. It almost returns to normal before it reaches the engine fan. On the other hand, the ESP design influences the generation of a circular density contour in front of the engine. It demonstrates that the vivo ESP discharge electrodes design has a significant aerodynamic influence at the front engine but only a minor impact after the engine fan, which is unlikely to have an effect on the engine's operation. Volcanic ash has a significant influence on the commercial aviation industry. On one occasion, the Eyjafjallajökull volcanic eruption cost up to 1.1 billion pounds, affecting 1.2 million passengers per day, accounting for 29% of worldwide aviation, and 10 million Pounds per day for Britain.

Table 2 Mass evaluation of ESP to specific engine model

ESP plate thickness	ESP mass of the usual flight (g)	ESP mass of the unusual flight (g)	Mass increase by percentage of usual flight (%)			Mass increase by percentage of unusual flight (%)		
			-94	-100	-112	-94	-100	-112
1 mm	2652.1	4651.2	0.062	0.045	0.036	0.109	0.079	0.063
2 mm	5304.1	9302.3	0.124	0.091	0.072	0.217	0.159	0.126
3 mm	7956.1	13953.4	0.186	0.136	0.108	0.325	0.238	0.189
4 mm	10608.1	18604.5	0.248	0.181	0.144	0.434	0.317	0.252
5 mm	13260.1	23255.6	0.309	0.226	0.179	0.541	0.396	0.314

In this study, the prospective technological strategy, an electrostatic precipitator (ESP), was customised for the high bypass turbofan engine model PW4000. It was based on the typical two-stage ESP, but with the PW4000 engine construction. The electrostatic part was developed with 20000 V voltage in this study, and contour of the electric potential is ideal distributed, indicating that an electric field may be properly provided under this ESP configuration design. The contour of the electric field in the ESP would have allowed to conclude on the potential of the electrostatic filter to mitigate the intake of volcanic ash in an engine.

Conclusion

The novel ESP prototype is mainly composed of a hexagram structure with six discharge electrode plates and 3 circular collection electrode rings. In this layout, the predicted mass gain does not exceed 0.55%, 25kg for one engine, and less than one baggage limit for a passenger. The maximum mass gain for one engine in normal flight is 13.3 kg with built-in ESP components and 23.3 kg in exceptional flight with complete ESP. Both masses are less than a passenger's baggage weight restriction (usually 25 kg). As a result, it is fair to disregard the ESP's mass influence during flight.

Acknowledgments

None.

Conflicts of interest

The author declares that there is no conflict of interest.

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