Theoretical aspects of an electrostatic aerosol filter for civilian turbofan engines

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***Abstract**: The paper addresses the problem of aerosol filtration in turbofan engines. The current problem of very fine aerosol admission is the impossibility for mechanical filtration; another aspect of the problem is the high mass flow of air to be filtered. Non-attended, the aerosol admission can -and usually does- lead to clogging of turbine cooling passages and can damage the engine completely. The approach is theoretical and relies on the principles of electrostatic dust collectors known in other industries. An estimative equation is deduced in order to quantify the electrical charge required to obtain the desired filtration. Although the device still needs more theoretical and experimental work, it could one day be used as a means of increasing the safety of airplanes passing trough an aerosol laden mass of air.*

***Key words**: turbofan engine, aerosol kinematics, electrostatic filtering, dust admission*

1. INTRODUCTION

One of the current unsolved problems of civilian aviation industry is operating safely in particle laden airflows such as dust storms or volcanic eruptions.

This is because most of the long and medium range aircraft use high bypass turbofan engines that require high mass flows of air – which cannot be properly filtered in order to eliminate unwanted particles Ref [1].

The main problems caused by particle admission in turbofan engines is air cooling passage clogging which can lead to turbine blade burnout or complete engine failure. This is because current turbofan engines have higher Turbine Inlet Temperatures than the super alloy of which the turbine is made can safely withstand – hence the need for internal turbine blade cooling Ref [2].

Sand particles can be filtered out of the turbine blade cooling passages Ref [3] and deposits may be avoided by optimizing the cooling film holes Ref [4]. However this is not the case with volcanic particles which have lower melting points and thus are more likely to adhere to the inside walls of the turbine blade.

Current high bypass turbofans draw cooling air form the High Pressure (HP) compressor, therefore it is more useful to try filter the core flow rather than the entire flow that passes trough the engine.

This is because the mechanical components that interact with the core flow are much more sensitive to damage from the particle deposition or erosion. It is also notable that the combustor which is the only one capable to melt the particles is also located in the core flow.

Small aerosol can only be filtered by electrostatic means Ref [5]. Therefore this paper proposes an electrostatic filtering system for the core flow of a high bypass turbofan engine.

2. THE PROPOSED SYSTEM

The electrostatic system is based on the static rejection principle of two particles with the same charge. Because air is a fairly good insulator, the only particles of the flow affected by electrostatic charges will be the volcanic ash particles. Figure 2 illustrates the fan major assembly and the passage to the high pressure compressor of a CFM 56 5a with suggested points of extraction via an electrostatic filter.

By charging the fan and LP compressor assembly with the same static charge two effects are obtained:

a. The dust particles will be rejected (at least in part) so they will be less impingent on the blades and vanes.

b. The blade system will act as a labyrinth with electrically charged walls which will provide enough exposure to the ash particles so that almost all of them will be charged at the exit point.

After exiting the LP compressor stage, the air goes trough a passage towards the HP compressor where the suggested electrostatic filter should be placed. The filter works by charging the exterior annulus with the opposite charge that has been applied thus far to the particles thus creating an attractive force and diverting them onto the exterior wall. To prevent accumulations we can provide a porous wall and a collector to continuously eject the ash accumulated on it.

The total mass of ash to be filtered, after 6 hours since the eruption, correspondent to the largest turbofan engine is of about 400 gr /sec. Given that the LP vane assembly for the CFM 56 is very dense consisting of 4 stators of 114, 128, 132 and 102 blades Ref [6], there is a high likelihood that the majority of the volcanic ash sucked into the booster at maximum throttle to be fully electrostatically charged. Thus the engine will not have to be throttled down too much in order to achieve complete filtering by the electrostatic system.

It should be noted that the fact that all blade/vane surfaces from the Fan and LP compressor are electrostatically charged with the same static charge of the aerosols will lead to aerosol rejection by said surfaces and hence reduce both erosion and fouling.

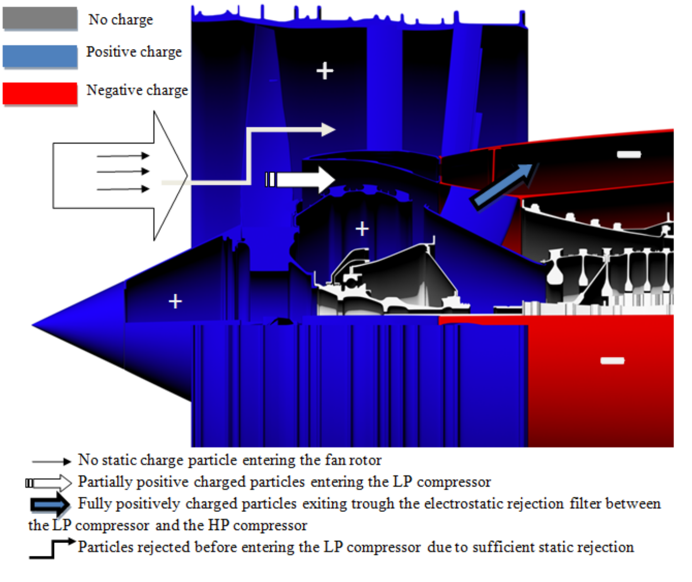

Fig. 1 The cutaway of a CFM 56-7 with polarization scheme and aerosol expected trajectories (blades are not shown in order to simplify the view)

3. A THEORETICAL CALCULATION

This proposed filtering safeguard is meant to achieve some degree of filtering in an otherwise impossible to filter aerosol. It is not meant however, as a foolproof all-weather, all-particle size filter but rather a filter for the very small volcanic dust particles that cannot be otherwise filtered by centrifugal forces exerted by the rotational flow field near a rotor.

Also, this filter system is not meant to be able to process high mass flows of volcanic dust, but rather to be able to provide prolonged operation while crossing a dispersed dust cloud.

The reasons for this strategy are complex but can be resumed as follows:

1.The very fine dust particles are the ones that stay airborne the longest, transforming a volcanic eruption into a prolonged crisis.

2.A dispersed cloud of dust particles can cover a much greater volume than a concentrated one.

3.Large particles can easily be filtered from the core flow by the fan rotor by centrifugal forces, diverting them into the secondary by-pass duct where the damage they can create are not critical for aviation safety, for instance to abrasion of probes and clogging of Helmholtz resonator panels.

4.The core flow has lower air mass flows therefore also lower masses of aerosols have to be processed.

5.Perhaps the most important aspect is the fact that an electrostatic filter will have absolutely no measurable effect upon the pressure recovery of the engine flows, or adverse impact on the aerodynamics of the bladed machinery.

The whole point of having an electrostatic filter for volcanic dust is to take advantage of the fact that the bladed network of both the fan major assembly and the low pressure compressor has very small gaps, i.e. distance between blades. Therefore because the aerosol loaded fluid has to flow between very narrow channels it is much easier for us to statically charge the volcanic dust-which is highly susceptible to electrostatic charging.

Moreover, because of the architecture of most of the high by pass turbofan engines, the duct linking the low pressure compressor to the high pressure compressor is a long hollow tube (more or less frusto-conical) which can house the dust retention system.

The retention system in itself is integrated in the walls of the duct between the LP compressor and the HP compressor; hence it will have little or no impact on the flow of air hence not damaging the turbofan engine performances.

The following calculations have been made considering a core flow of 100 kg/sec of air, at an altitude h_b.

The power required to physically remove the mass of suspended dust particles:

$$P = \dot{m} \cdot \left(\frac{\Delta x}{\tau} \right)^2 \tag{1}$$

$$\tau = \frac{v_{stream}}{l_{duct}} \tag{2}$$

Δx is the equivalent mean distance for a particle to reach the outer wall collector

v_{stream} is the velocity of the flow through the linking duct

l_{duct} is the total length of the duct that links the LP compressor to the HP compressor

For a simplified annular section, Δx is given:

$$\Delta x = R_{ext} - \sqrt{\frac{R_{ext}^2 - R_{\text{int}}^2}{2}} \tag{3}$$

and for this example it will be $\Delta x = 15cm$

$\dot{m}$ is the mass of the aerosol to be filtered

Considering the variation of density with altitude designated by subscript b:

$$\rho = \rho_b \left[\frac{T_b + L_b(h - h_b)}{T_b} \right]^{\left(-\frac{g_0 M}{R^* L_b}\right) - 1} \tag{4}$$

ρ = Mass density (kg/m^3)
T = Standard temperature (K)
L = Standard temperature lapse rate -0.0065 (K/m) in ISA
h = Height above sea level (geopotential meters)
R^* = Universal gas constant for air: 8.31432 N·m/(mol·K)
g_0 = Gravitational acceleration (9.80665 m/s^2)
M = Molar mass of the Earth's air (0.0289644 kg/mol)

We can deduce the volume of air intake at the altitude b in one second of operation:

$$\dot{V}_{air\_aerosol} = \frac{\dot{m}_{air}}{\rho_b} \tag{5}$$

Knowing the particle density of the dust will provide us with the total mass of the intake of dust in one second of operation:

$$\dot{m}_{dust} = \rho_{dust/volume} \cdot \frac{\dot{m}_{air}}{\rho_b} \tag{6}$$

Details regarding the volcanic dust density is take from Ref [7] which gives 0.2-0,6 g/m^3 after March 19, 1982 ash eruption of Mount St. Helens.

Considering this, an estimate can be made about the mass of intake of particles on the core flow at a given flight level of 35,000 ft:

ρ_b =0.38 kg/m^3

$\dot{m}_{dust}$ =52.58 g/sec to 150 g/sec

This value is valid only in this example and should only be taken as a case study. Therefore, depending on the engine geometry, engine operational parameters and the weather conditions including the volcanic eruption, we can estimate the effort needed to filter out the dust particles for the core flow alone:

Assuming a $\Delta x = 15cm$ and $\dot{m}_{dust}$ =0.1 kg/sec, the power required ideally is:

P~ 2.5 [W] Which is insignificant to any turbofan engine.

As it was shown earlier, the ideal power required to filter all of the volcanic dust is relatively small for a dispersed cloud.

However it is necessary to see the efficiency with which this power is delivered in order to estimate the true power consumed by the system.

For preliminary calculations although, we shall prefer Ref [8]:

$$v = \frac{eE}{6\pi\alpha\eta} \tag{7}$$

This Stockes equation links the velocity v to the radius of the particle a, the electric charge of the particle e, and the dynamic viscosity of the fluid η, E is the intensity of the field in which the particle is assumed to be moving uniformly.

This is only a simplification.

We will consider the dynamic (total) viscosity of 0.6924 *(kg/m s) x 10*$^{-5}$.

Volcanic dust particles have diameters of approximate 60 microns Ref [8].

The velocity required for the filter to be effective is dependent on the flow velocity of the air trough the connecting LP C-HP C duct, the length of the duct itself and the Δx the particles have to travel:

$$v_{required} = \Delta x \frac{v_{stream}}{l_{duct}} \tag{8}$$

Thus:

$$eE = 6\pi\alpha\eta\Delta x \frac{v_{stream}}{l_{duct}} \tag{9}$$

v_{stream} =150 m/sec

l_{duct} =0.5 m

a=310^{-5} m

η=0.6924 *(kg/m s) x 10*$^{-5}$

$\Delta x = 15cm$

The electric charge of the particle depends on the efficiency of the electrostatic induction made trough the blade network of the fan and LP compressor.

The intensity of the electrostatic field created by the duct walls can also be modified for better filtration.

Another way to go about calculating the parameters of the electrostatic field is to use Coulomb law:

The force exerted between two points of charges $Q_{particle}$ and Q_{wall} is:

$$F = \frac{Q_{particle} Q_{wall}}{4\pi\Delta x^2 \varepsilon_{air}} \tag{10}$$

where $\Delta x = 15cm$ is the distance and epsilon is the permittivity of air.

From the power requirement in Eq. 1, Q_{wall} achievable at the wall we can deduce $Q_{particle}$ for the particles of dust:

$$P_{required} = F \cdot \Delta x \cdot \frac{v_{stream}}{l_{duct}} \tag{11}$$

Where the first term is the Coulomb force, the second is the distance over which it is exerted and the last ratio is the time duration available for the action.

Therefore:

$$P = \dot{m} \cdot \left(\frac{\Delta x}{\tau}\right)^2 = \frac{Q_{particle} Q_{wall}}{4\pi \Delta x^2 \varepsilon_{air}} \cdot \Delta x \cdot \frac{v_{stream}}{l_{duct}} \tag{12}$$

$$Q_{particle} = \frac{1}{Q_{wall}} \dot{m}_{dust} \left(\frac{\Delta x}{\tau}\right)^2 4\pi \Delta x \varepsilon_{air} \tag{13}$$

Meaning that the efficiency of the electrostatic induction must be

$$\frac{Q_{particle}}{Q_{wall}} = \frac{1}{Q_{wall}^2} \dot{m}_{dust} \left(\frac{\Delta x}{\tau}\right)^2 4\pi \Delta x \varepsilon_{air} \tag{14}$$

We will end this note by laying out once more the way to carry out this effect mitigation system:

We stress the fact that in the intake stream there is absolutely no mechanical part other than the blades of the original fan and LP compressor, the fan and LP compressor assembly become integrating part of the system.

The role of both the fan rotor and the LP compressor rotor and stator is to provide the volcanic dust particles with enough exposure to the electrostatic field so that the electrostatic induction process will induce a high enough electrostatic charge to the dust particles.

The duct that connects the LP compressor to the HP compressor is also unchanged from the aerodynamic stand point. The only modification is that the inner diameter walls are electrostatically charged with the same electrostatic charge induced to the particles so that it will reject the particles by Coulombian force and that the outer wall of the duct is electrostatically charged with an opposite charge of that induced to the particles in order to attract them towards it. Another particular aspect of this effect mitigation system is that the outer wall is porous as to allow drawn particles to be collected within a controlled plenum and there from expelled trough a pump system out the bypass duct.

It is reasonable to assume that some particles will be subject to electrostatic rejection before entering the LP compressor due to a combination of quick electrostatic induction and centrifugation and therefore those particles have been depicted in Fig.2.

4. RETROFITTING THE SYSTEM TO EXISTING TURBOFAN ENGINES

In order to minimize energy usage and also keep the engineering and certification effort to a minimum we must insulate the fan and LP compressor rotor from the rest of the engine. To achieve this, we could add an insulating material gasket to the LP and Fan major assembly while also using insulator washers and Teflon coatings for the assembly bolts.

The stator assembly of the LP compressor can also be insulated at the assembly point using insulator gaskets, washers and tefloned bolts.

The electrostatic charge could be provided by a wire coupling from a van der Graff generator or any similar high voltage-low power electrostatic device.

As stated before, the volcanic ash particles are highly susceptible to electrostatic charges, as opposed to air molecules.

Hence this arrangement will prove useful in filtering aerosols while leaving the airflow largely intact.

The filter works by two mechanisms:

1. Static rejection of the aerosols before the enter the booster core flow
2. Static suction in the transition duct between the LP and HP compressor

It is this second mechanism that will require more close attention as it implies the use of an aerosol trap and ejector that will have to be integrated in the already existing engine.

Off course all modifications must be certified and be included within the operation and maintenance manual of each individual engine however, as an estimate, the skill requirements for this retrofitting would rise to line maintenance only so it should be easy to implement on a moment's notice on within any maintenance organization.

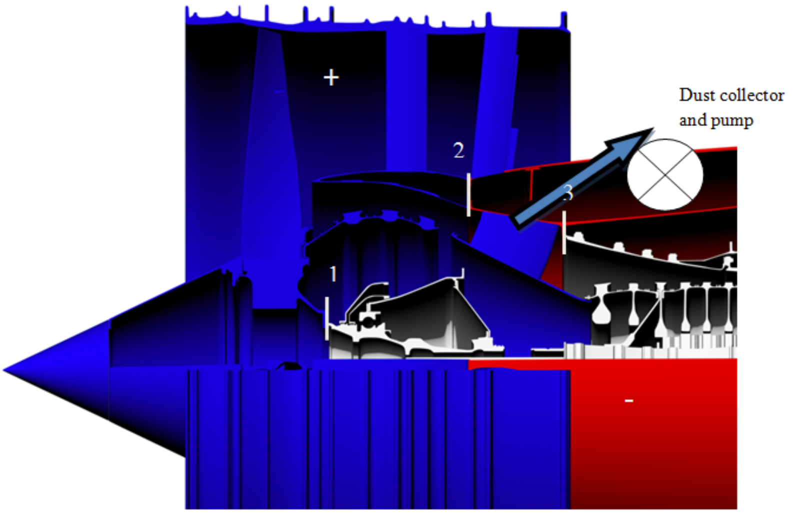

Fig. 2 Locations of retrofitting for Electrostatic Core Filtering System (Insulator gasket, washers and bolts 1, 2, 3) Electrostatic charge delivery system : trough the fan stator ->spliter lip, LP vanes, ->fan rotor-fan hub->LP rotor

5. FURTHER WORK

In order to validate the above described system, a series of computational fluid dynamics testing should be performed, followed by experimental and finally certification testings.

The CFD testing should be able to account for both the electrostatic charging of the aerosol and also its lift and drag coefficients.

It is known for a fact that various sizes and geometries of aerosol particles have different behaviors in the boundary layer Ref [9]. It is therefore required to analyze various concentration distributions of aerosol particles in order to calibrate the filtering system to operate at maximum efficiency for each situation it faces.

Also it is necessary to accurately model the two-phase flows that the engine encounters. This is particularly difficult since conventional Eulerian solvers have problems in tracking the solid particles.

Hence in this case we would suggest either a full Lagrangean method such as SPH (Smoothed Particle Hydrodynamics) or a combined Euler-Lagrange model.

Lattice Boltzmann methods may be used i.e. Boltzmann transport equation instead of Navier-Stokes as it has significant advantages in the study of complex flows such as two-phase aerosol laden air Ref [10].

In all cases it is clear that also more physical testing should be performed in order to classify and quantify the various aerosol particles the airplane is likely to encounter be it from natural causes such as dust storms or volcanic eruptions or man-made such as industrial accidents.

6. CONCLUSIONS

A new type of filtration device for turbofan engines has been described. Such a system would make use of the blade network of the Fan and LP in order to charge the aerosol particles. Then, the charged particles would pass through the duct that links the LP and HP compressor, there the outer wall will have an opposite charge attracting the particles into the dust collector which will collect them and either disperse them into the fan discharge or retain them inside a purpose-built tank.

The setup envisioned requires only a few modifications to the existing conventional turbofan engines, consisting in :

1. An electrostatic generator for charging the surfaces
2. A dust collector and disperser located in the duct that links the Low Pressure and High Pressure Compressors
3. Electrical insulator gaskets, washers and bolts to insulate the charged parts of the Fan major module form the rest of the engine which does not need any electric charge.

A simple mathematical formula has been deduced in order to estimate the charges required for this system. Although the principle appears to be simple to implement, specific details must first be obtained through CFD studies and experimental tests in order to make sure that the device itself is of no threat to aviation safety and also that it is efficient enough to carry out the desired task.

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