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# Fuel and emission reduction assessment for civil aircraft engine fleet on-wing washing

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ABSTRACT

On-wing washing for civil aviation engine is an important approach to improve the Exhaust Gas Temperature Margin (EGTM), and to reduce the fuel consumption as well as the resultant aviation emission. In view of the fuel flow reduction achieved by on-wing washing, this study proposes an estimation method of engine performance improvement due to washing according to fleet fuel consumption savings and engine washing costs. Finally, the engine washing interval of a fleet can be optimized based on the proposed performance assessment method of on-wing washing. A case study of one airline fleet of 200 CFM56 Engines demonstrates the effectiveness of the proposed method. The results show that the optimal washing interval is 3 times a year, and that an average annual cost savings of 20.15 million dollars can be achieved by reducing 5471 ton fuel consumption and 17,250 ton $CO_2$ emission.

## 1. Introduction

Gas turbines of civil aircraft become contaminated during normal operations due to airborne particles (such as sand, airborne dust, soot and emissions from power plants and automobiles, etc.) accumulated on the blade and annulus surface, which may lead to the reduction of compressor efficiency and airflow capacity, and the increases in exhaust gas temperature (EGT) and fuel consumption. Short-range single-aisle passenger aircrafts, which are operated with higher frequency of take-off and landing phases in the lower atmosphere, are much more susceptible to engine contamination problem compared to their long-haul intercontinental counter-part. The particles accumulation on the airfoils surface leads to the surface roughness as well as the airfoils' shape changing, therefore decreasing the engine efficiency and distorting the blade aerodynamics (Diakunchak, 1992). In this case, the control system of the fouled engine has to increase the fuel flow to meet the required thrust during the flight, therefore increasing the EGT, which may further speed up the life consumption of the hot section components (Igie et al., 2016).

The increased fuel consumption caused by the engine contamination will also produce more aviation emissions such as carbon dioxide ($CO_2$), nitrogen oxides ($NO_x$), carbon monoxide (CO), sulfur oxides ($SO_x$), and unburned or partially combusted hydrocarbons (Sutkus et al., 2001). These emissions, depending on whether they are emitted near the ground or at altitude, are primarily considered as local air quality pollutants or greenhouse gases, respectively. Aviation emissions, generated near the airport ground during aircraft's LTO (Land and Take-Off) phases, are closely related to air pollution and public health (Yim et al., 2015; Huss et al., 2010). On the other side, aviation emissions emitted in en-route airspace during the cruise phase have significant effects on the shift of the chemical and particle microphysical properties of the atmosphere and, consequently, climate change (Lee et al., 2009; Chen et al.,

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2016). Therefore, it is important to reduce the aviation emissions in order to relieve their impact on public health and greenhouse effect.

Aviation is responsible for 13% of transportation-related fossil fuel consumptions and 2% of all anthropogenic carbon dioxide emissions (Brasseur and Gupta, 2010). Additionally, global air traffic is expected to increase with an annual growth rate of 5.8% over the next two decades, which means a great increase in fuel consumptions and carbon dioxide emissions due to engine performance degradation (Airbus). Technological and operational measures are, thereby, adopted by aircraft and engine manufactures and operators to reduce the fuel consumptions as well as the carbon dioxide emissions, which can neutralize negative effects caused by the engine contamination problem. On-wing water washing is an efficient and economy-friendly method to improve the engine performance in practice, which ultimately contributed to the fuel burn saving and emission reduction (Ujam and Ekere, 2013; Grampella et al., 2017).

The past few decades have witnessed increased interest in developing on-wing washing method for aviation engines, which is an effective approach to mitigating the performance deterioration caused by engine contamination. Mund et al. reviewed the compressor on-wing washing methods, the systems developments and the trends based on the related open literatures and patents (Mund and Pilidis, 2006). Boyce et al. proposed a test method of industrial turbines to identify the proper washing frequency as well as the dissolving solvents, where the compressor isentropic efficiency, the heat rate, and the thermal efficiency were used to assess the performance of engine washing (Boyce and Gonzalez, 2007). Syverud et al. reported the results of a series of on-wing water washing tests on a jet engine, where the engine was washed with different droplet sizes and water-to-air mass ratios. The test results show that the performance of on-wing washing is closely related to the water-to-air mass ratio (Syverud and Bakken, 2007). Brun et al. studied the effectiveness of on-wing compressor washing using various purity grade waters and washing detergents. The results showed that the blade cleaning is primarily a mechanical function and the performance does not depend on the type of fluid used for cleaning. The study found that the blade erosion was not a significant issue for the short on-wing washing durations. However, uncontrolled water-washing for extended periods of time may result in blade edge erosions (Brun et al., 2015). Giesecke et al. developed a techno-economic model of a short-range aero engine to study the benefit for different washing intervals. The results show that a gross recovery of almost £75,000 per year for a short-range engine is achieved with a marginal increase of the total washing cost (Giesecke et al., 2012). Roupa et al. investigated the cleaning effectiveness of on-wing washing for removing foulants composed of crude oil and carbon particles (Roupa et al., 2013). Schneider et al. carried out a throughout analysis to study the effects of engine on-wing washing on the gas turbine performance improvements (Schneider et al., 2010; Ogbonnaya, 2011). Need et al. analyzed the reliability of a gas turbine water washing system used on different types of engines (Need et al., 2015).

On-wing engine washing is regularly carried out by the airline operators, which have proved to be an effective way to improve the engine performance and to save the airline operational cost related to the compressor fouling. A general washing interval, e.g., from 3 to 8 months, are typically recommended by the engine OEMs for each type of engine. However, the performance of on-wing washing and the optimum washing interval is influenced by a number of factors, including the number of flight cycles, the exhaust gas temperature margin, types of operation environment, physical condition of the compressor, etc. (Igie, 2017). Accurate estimation of performance improvement of on-wing washing and optimization of washing intervals are thus important to ensure efficient and economic operation of aircraft fleet, which have not been studied before. Motivated by this observation, this paper aims to address the method for the fuel and emission reduction assessment resulting from engine fleet on-wing water washing. The method proposed in this paper can be applied to assist airlines in optimizing on-wing washing intervals in specific operation conditions by quantitatively assessing the engine performance improvement due to washing from an economic perspective.

This study proposes a quantitative assessment method for fuel and emission reduction resulting from on-wing washing of civil aircraft engine. Then the optimal wash interval is determined based on the trade off on the benefit and cost of water washing. The rest of this paper is organized as follows. Section 2 studies the effects of on-wing water washing on the engine performance and the emitted emission of a civil aircraft. Then a quantitative assessment method for fuel consumption savings and carbon dioxide emission reduction due to engine on-wing water washing is proposed in Section 3. A case study on a two spool turbo fan engine is carried out to demonstrate the effectivity of the estimation method proposed in this paper. The case study also presents a trade-off on benefit and cost of engine on-wing water washing to derive the optimal washing Interval. Finally, conclusions are drawn in Section 4.

## 2. Effects of engine on-wing water washing

### 2.1. Exhaust gas temperature margin

As the service time of the aviation engines increases, performance deterioration caused by the abrasion/erosion of the components becomes one of the main reasons of engine removal in actual operation. To provide the same thrust, a deteriorated engine will consume more fuel, thus increasing the exhaust gas temperature (EGT), and decreasing the exhaust gas temperature margin (EGTM):

$$EGTM = EGT_{red} - EGT_e$$

where $EGT_{red}$ is the red line temperature of the engine, set by the manufacturer; $EGT_e$ is the exhaust gas temperature of the engine, which is measured under the reference condition (sea-level atmosphere, corner point temperature) during take-off at the maximum power. Besides the performance deterioration of the engine, other factors such as operational environments, take-off conditions, engine bleed air and sensor noise also influence the EGTM, causing the final EGTM data to have rather large noise and great dispersion. It can be seen from this equation that the EGTM decreases as the performance of the on-wing engine deteriorates. Therefore, the EGTM can be used to estimate the deterioration of the engine performance. Additionally, the EGTM can also be used as