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A gaseous emissions analysis of commercial aircraft engines during test-cell run

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HIGHLIGHTS

- Consideration of newly-overhauled engines, unique sample probe location.
- Gaseous emission measurements with continuous data (idle to maximum power).
- Quantification of cold and hot idle difference, NO_2/NO_x ratios, ICAO comparison.
- Combustor inlet and ambient air temperatures effects on emissions.

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ABSTRACT

This study presents an analysis of the seventeen complete measurements of gaseous emissions of eleven different CFM56-7B26 turbofan engines during the regular test-cell runs. A novel measurement setup is established in which the sample probe is located immediately behind the low pressure turbine rotor. Recording a total of 49,190 data points for 26 raw variables (obtained from both the emission measurement and engine test systems), emissions are characterized with stable engine power settings representing main flight phases, as well as fuel flow of the engine during the entire run. Carbon monoxide and total hydrocarbons concentrations are found to be a strong function of fuel flow at low power settings, and nitrogen oxides emissions at high power settings. In comparison to emission indices provided by the International Civil Aviation Organization, the current study results in considerably higher carbon monoxide and hydrocarbons under idle conditions, with relatively lower nitrogen oxides at almost all of the power settings. On the other hand, significant differences in levels of nitrogen oxides are observed from one engine test to another, emphasizing the effects of the engine and the ambient air conditions. The average NO_2/NO_x are found to be 40% (±16) and 32% (±9) for ground and approach idles, respectively, while at high power settings, above N1 = 64%, the NO_2/NO_x ratios stabilize at around 5–6% (±1–2). Since the emissions were monitored and recorded during the entire engine run, the start and end moments (cold and hot idles) of the tests are compared. The average carbon monoxide and hydrocarbons concentrations are found to be 14% and 35% lower at hot ground idles compared to cold ground idle, with the results for nitrogen oxides and carbon dioxide being 22% and 0.5% higher. The effect of ambient air temperature on emissions are also investigated and quantified for certain temperature ranges. It has been determined that the hydrocarbons and carbon monoxide concentrations decrease with ambient air temperature, yet the nitrogen oxides and carbon dioxide concentrations increase. Findings related to ambient air temperature are found to corroborate the findings related to running at cold and hot idles, linking to a positive correlation between the ambient air temperature, the combustor inlet temperature and the exhaust gas temperature.

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1. Introduction

In commercial aviation, the current production rate for the B737 and A320 has surpassed one aircraft per day in response to increasing demand. Future projections provided by the International Civil Aviation Organization (ICAO) forecast that the number of passengers using air transportation will double that of 2013 by 2030, reaching 6.4 billion. The number of departures in 2013 is recorded at around 33 million, which is more than one million flights more compared to those for 2012 (ICAO, 2014). With regard to the manufacturing, Airbus projections estimate that more than 31,000 new aircraft will be built by 2032 (Airbus, 2014), with Boeing topping this estimate, forecasting 36,000 new aircraft by 2033 (Boeing, 2014). These projections imply double the current fleet capacity over the next 20 years. As a result, major areas of current concern, such as safety, capacity, fuel cost and environmental issues appear to be much more significant in the near future.

Of these predictable side effects, the environmental impact of aviation may be one most difficult to measure over time. As a greenhouse gas, CO_2 and its output through aviation is well understood, mainly due to its clear dependence on the fuel consumption. For instance, certain airlines publish the carbon footprints of individual flight routes, leading to an increased level of awareness. Focusing on new generation air traffic management systems in one side, experimental research on sustainable fuels or replacing the conventional operational procedures with more economical and environmentally friendly ones (from weight reduction strategies to single engine taxiing) have been investigating and implementing by aviation stakeholders. Clearly, as a result of such efforts, each percentage efficiency rise leads to less CO_2 emissions. However, it seems that there is a lack of consensus on other gaseous and particulate matter emissions, since their formation cannot be determined in as straightforward a manner as that of CO_2, as well as the fact that they incorporate a large number of variables and uncertainties. Nonetheless, despite these complexities and certain challenges to the performance of experimental research on aircraft, a large number of working groups have been endeavoring to better characterize aircraft emissions.

A number of these studies focus on local air quality or general pollutant formation in the vicinity of an airport, using different measurement methods. Among these methods are on-wing (Anderson et al., 2006; Wey et al., 2007; Wormhoudt et al., 2007; Agrawal et al., 2008; Corporan et al., 2008; Durdina et al., 2014), test-cell (Cox et al., 1972; Diehl, 1973; Holdeman, 1974; Lyon et al., 1980; Spicer et al., 1984), in-flight (Miller, 2003) and remote sampling (Schafer et al., 2003; Johnson et al., 2008). Certain other studies show particular interest in environmental effects in a broader sense and attempt to investigate either the regional (Kesgin, 2006; Stettler et al., 2011; Fan et al., 2012; Song and Shon, 2012; Yim et al., 2013) or global (Baughcum et al., 1996; Gardner et al., 1997; Sutkus et al., 2001) impact of aviation. Regardless of the scope and approach chosen, the main challenge of all these studies lies in the uncertainties on the impact. Hence, studies relating to the quantification and measurement of aircraft emissions, considering real world conditions, are thought to be essential in reducing the existing uncertainties.

In this respect, the present study focuses on the fundamental results of a gaseous emissions measurements campaign of eleven newly-overhauled CFM56-7B26 turbofan engines during a regular engine run test at a test-cell facility. The approach brings together several novel features. Firstly, the sample probe used for the measurements was installed inside the engine exhaust section, on the turbine rear frame, behind the last stage of the low pressure turbine rotor. Hence, the potential effects of fan by-pass or ambient air were eliminated. Secondly, the measurements were performed on newly-overhauled older engines. This enabled us to incorporate average world aircraft engine conditions, implying neither brand new engines nor engines at maximum deterioration. Thirdly, a practical measurement setup was established, allowing for the measurements of different engines without major adjustments. In addition, for some tests, engines were run subsequently two or three times, enabling a complete verification regarding the repeatability of the results, as well as observation of the effects of certain external factors. As a second objective of this study, the potential effects of ambient air temperature (T_{amb}) and the differences between cold and hot idles are also examined. Finally, another important feature to be noted is a better characterization of the emissions at high power run, since an engine high power run in a test-cell provides safer, easier and longer periods of measurements to make reliable determinations.

2. Background and dataset

This study is based on the results of a recently completed aircraft engine emissions project. In this project, 25 full emissions measurements were performed in collaboration with Turkish Airlines (THY), the national flag carrier of Turkey, and Turkish Technic, the maintenance company, on four different types of CFM56 engines (CFM56-3B1, -3B2, -7B24 and -7B26) and fourteen different engines, during the test-cell run. Therefore, the results are for old engines that had been newly-overhauled. Some of the engines were tested more than once, providing the opportunity to observe the effects of ambient conditions or to verify the results in subsequent measurements.

Fundamental aspects of the measurement setup are noted as follows. The sample probe, a modified engine temperature sensor, was installed inside the exhaust section, in a pressure sensor housing. Samples were transferred through a 25 m sample heated line (160 ± 15 °C), except for the first part which remained inside the engine cowling, as it was hot enough to keep the sample above the dew point. The main driving force in the sampling line was a dump pump used to speed up the sample so that it reached the analyzers in less than 10 s, to dump the excess sample, and to direct the sample to the $CO-CO_2$ analyzer, since this analyzer does not need a heated sample. There was also a gas control and conditioning unit, including switches for sampling and calibration, as well as driers for the $CO-CO_2$ and NOx analyzers.

The total HC analyzer was a Teledyne 4030 analyzer equipped with a flame ionization detector. The THC analyzer uses H2 as fuel and N2 as a carrier gas. The $CO-CO_2$ analyzer was a Teledyne 7500 non-dispersive infrared absorption analyzer. The NOx ($NO-NO_2-NO_x$) analyzer was a Teledyne 9110 TH chemiluminescense analyzer. Water vapor was removed from the samples using Perma Pure driers before the $CO-CO_2$ and NO_x analysis. Certain key features of the analyzers and sampling conditions are shown in Table 1. Details of the emissions measurement setup, the emissions indices calculations and the referencing of ambient condition corrections, as well as the results for other types of engines in the same project are available elsewhere (Turgut et al., 2015).

Data related to the emissions measurements are summarized in Table 2. The measurements started in May 2013, and ended in May 2014, with the test location at Ataturk International Airport, Istanbul, Turkey. Noting that only the CFM56-7B26 engines are considered in the current study, in the following sections, the measurement results for CO_2, CO, HC, NO_2, NO and NO_x emissions of seventeen full tests on eleven different engine are discussed.

In a typical engine test, there are several stable power settings runs with appropriate acceleration and deceleration procedures, in