ASME Paper Title: Case for exploring compressor water injection for airport emission reduction

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ASME Journal Title: ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition

Volume/Issue _Vol. 3___________________________ Date of Publication (VOR* Online) _30 June 2017______

ASME Digital Collection URL: http://proceedings.asmedigitalcollection.asme.org/proceeding.aspx?articleid=2649857

DOI: 10.1115/GT2017-64780

ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition, 26-30 June 2017, Charlotte, USA.
DOI:10.1115/GT2017-64780. ISBN:978-079185083-1

GT2017-64780

CASE FOR EXPLORING COMPRESSOR WATER INJECTION FOR AIRPORT EMISSION REDUCTION

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ABSTRACT

The increasing world population, higher accessibility to air transportation, coupled with new low-cost airline models has resulted in an unprecedented increase in demand for civil aviation. The industry is currently experiencing a global increase of operational civil aircraft at a rate of 5-6% annually. This growth suggests a vibrant future for the industry, however, the environmental implications and the footprint is worth considerable attention given the expected scale of growth in the industry and the possible side effects to human health. The stakeholders involved, some of which include: airports and airline operators, jet engine and airframe manufacturers and various government bodies, are introducing measures in order to mitigate the increase in certain emissions and hence their impact.

This study focuses on one of the many existing approaches targeting the reduction in gaseous emissions, predominantly nitrogen oxides (NO_x). This is through compressor water injection that is estimated to reduce NO_x emissions by almost half under certain ambient conditions and water-to-air ratio. Apart from reviewing this technology, the study, more importantly, presents the ideas in relation to other major existing approaches/concepts.

It would be observed that compressor water injection can be more readily applied to the existing infrastructure when compared to other approaches. This technique is one of the most promising methods for reducing NO_x emissions, an area of particular importance given that modern engines, though more thermally efficient, operate at higher pressure ratios and flame temperature, both of which enhance nitrogen oxides formation.

One of the main contributions of this paper is the categorisation of existing approaches focused on reducing aircraft-borne airport emissions. Different technologies and operational changes are classified according to the key pollutants that they target with respect to the landing and take-off cycle based on 11 different engine types. These gaseous-emissions mitigating approaches are analyzed based on their individual merits, limitations and feasibilities. Compressor water injection is re-introduced here as a more readily applicable solution despite its technological challenges, many of which can be better resolved with today's knowledge.

INTRODUCTION

Civil aviation accounts for 13% of transportation greenhouse gas emissions in Europe [1,2] and 7% of total European NO_x emissions [3]. At Heathrow airport and surrounding areas, 53% of air pollutants come from air traffic [4], and evidence reveals that this number can be in the order of 60% - 80% in other airports around the world [5,6]. Aircraft-related contaminants are likely to overtake motor vehicle pollutants in the near future [7]. Currently, around 3% of the overall carbon dioxide (CO_2) production by man-made activities comes from civilian jet fuel burn and that number is likely to increase with increasing air travel demand. Macintosh [8] indicates that international aviation carbon dioxide emissions could increase by more than 110% between 2005 and 2025 despite technological developments. Air transportation in North America, Europe, Asia and the Middle east is bound to increase in 5.7%, 5.0%, 8.8% and 10% respectively [9]. Experts predict a worldwide rise in demand of over 5% for international travel and 4.4% for domestic traffic, suggesting that passenger air traffic will double every 14 years [3,10]. In terms of passenger flow, civil aviation transports more people than ever before and around 2 billion passengers fly on scheduled flights annually with predictions of a rise of up to 7 billion by 2034 [11]; some sources predict 9 billion passengers by 2025 [12]. Sgouridis et al. [9] predict that aviation contribution to total European Union emissions could reach anywhere between 10%

to 50% by 2050. Aircraft-related ground gaseous emissions have received considerable attention in previous years, especially for NO_x emissions. Modern aircraft engines, despite being more thermally efficient, tend to produce more NO_x due to the dependency of this emission with Combustion Chamber (CC) exit temperature[13,14]. The trend of engines that produce high levels of NO_x is reduced by newer CC designs, but not sufficiently enough, considering the high rise on aviation demand[3]. The environmental implications of aircraft pollutants and effects on the human health and the environment can be found in [6,10,15–18], and include respiratory illness, acidification of freshwater reservoirs and damage to the local vegetation and wildlife.

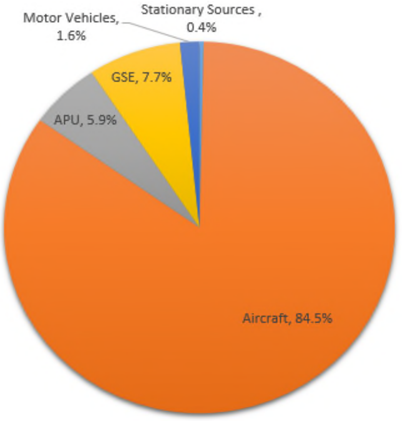

Figure 1 Source of pollutants in Atlanta international Airport [19]

ICAO [3] has identified aircraft engines to be the dominant airport-related source of air contaminants. In the busiest airport in the world: Hartsfield-Jackson international airport in Atlanta, jet fuel burn accounts for 84.5% of the total airport emissions [19] as shown in Fig. 1. Figure 2 shows the sources of air pollution at Heathrow airport as well as the segments of aircraft engine activity. It can be seen that over half of the total air pollutants are from aero-engines, of which almost 50% is during take-off roll. Based on the experimental data taken at 8 locations around Heathrow airport, Carlsaw et al. [20] indicate that the airport is responsible for 23% of the NO_x in the air around the area, while the Heathrow study indicates about 50% [4].

Stettler et al. [6] taking into account 20 of the busiest airports in the UK, concluded that around 72% of NO_x emissions are produced at take-off and climb (10% at taxi and 18% at landing). Daggett et al. [21] estimate similar emission inventories taking into account taxi, climb, take-off and landing as shown in Fig. 3. The opposite is the case for other contaminants like CO, where the highest levels are found at low power settings like taxiing.

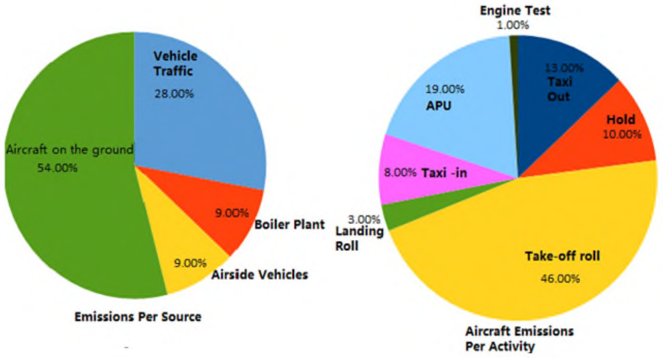

Figure 2 Heathrow airport emissions by source and aircraft activity [4]

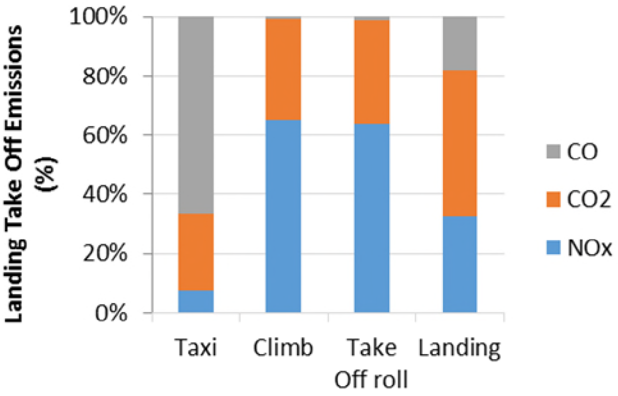

Figure 3 Airport emissions by type and activity [21]

Some of the main aviation pollutants have been mentioned (CO, CO_2 and NO_x) and others include Unburned Hydrocarbons (UHC), Particulate Matter (C) and Oxides of Sulfur (SO_x). An extensive review of airport-related pollutants and their sources can be found in [22]. Figure 4 presents a general overview of some of the key aero-engine pollutant emissions as a function of engine power setting. CO which is produced as a result of unburned hydrocarbons due to inadequate mixing of fuel and air, quenching of post-flame products or CO_2 dissociation [23], is higher at lower power setting (taxing and idle) or low speeds. Lefebvre [7] notes that most modern combustor designs can already achieve 99% combustion efficiency at design point (typically cruise – around 20 to 30% of take-off thrust), and thus the CO production at this flight stage will be minimum. NO_x is a combination of Nitrogen Oxide (NO) and Nitrogen Dioxide (NO_2) and can be formed by either endothermic reactions in the combustion chamber, oxide mechanisms, prompt NO or fuel NO [24].

As indicated in Fig. 4, NO_x increases with increasing power thus its production rate is highest under take-off and climb flight phases. The reason being that NO_x is proportional to gas pressure and temperature, as well as residence time. Following the smoke crisis in Los Angeles in the 1970s, Lipfert [25] conducted studies correlating NO_x production with combustor inlet temperature for different engine models. From the work done by Lipfert [25], Maughan et al. [26] proposed correlations of NO_x formations as a function of combustion pressure and temperature. Lefebvre [7] also proposes a mathematical relationship between NO_x and pressure ratio. This indicates that aero-engines with higher pressure ratios or operating at higher temperatures will produce more NO_x emissions.

CO_2 is produced as a consequence of the complete burn of any fuel containing carbon [23]; as long as there is combustion there will be CO_2. A reduction of aviation CO_2 can be achieved by increasing the thermodynamic efficiency of the engines, shorter waiting times or improving the operations of the aircraft.

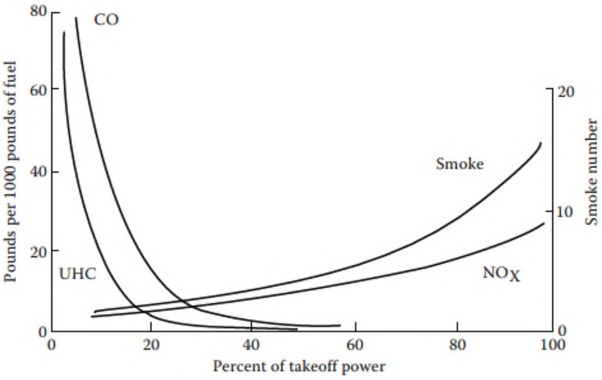

Figure 4: Different Emissions as a percent of take-off power [7].

MEASURES FOR MITIGATING AIRPORT-RELATED EMISSIONS

Current measures in tackling airport-related air pollutants can be broadly classified as operational, technological or a mixture of both. Operational solutions are defined here as those approaches in which there are no fundamental changes to the aircraft or the engines, and thus require very little investment and developing time. This category is on the left-hand side of Fig. 5 and can be implemented by modifying the management of the aircraft. Most of the operational changes proposed in the open literature are based on reducing the time the engines run at low power settings such as idling or taxi as indicated in Fig. 5 which highlights technologies/approaches addressing these activities with a surrounding dashed line. These alternatives have great potential for CO and HC reductions (applicable to operations on the left-hand side in Fig. 4) but do little to reduce $NO_{x.}$ Nevertheless, the reductions in emissions during idle/taxi are important, given the typical length of the time duration of a Landing and Take-Off (LTO) cycle as indicated in Table 1.

On the other hand, technological solutions are indicated on the right-hand side of Fig.5. These are those approaches for which considerable alterations to the aircraft are necessary. They often involve very lengthy times in development and certification, usually requiring modifications of aircraft and airport infrastructure to accommodate for the changes. As a result, they are capital intensive for the respective stakeholders involved. From Fig. 5 it can be observed that in the classification, technological approaches can involve reductions during take-off or taxi mode operation

Between these two extremes in the classification, are approaches that consist of both features. This category is effectively technological, but require less transformation to the engines or the airframe as compared to the purely technological approach. As a result, these initiatives require minor operational adaptations.

Table 1 Landing/Take-Off Cycle (ICAO) [27]

Mode	**Time (min)**	**Thrust**
Take-off	0.7	100%
Climb	2.2	85%
Approach	4.0	30%
Idle/taxi	26.0	7%

Each pie chart in Fig. 5 represents a different airport emission-mitigating approach. The impact on HC, CO, and NO_x is based on the ICAO engine emission data bank [28].The size of each pie chart relates to the impact on the main tackled emission reduction. Further details of the calculations can be found in the Appendix. The relative proportion of each segment of the pie chart shown in different colour indicates the pollutant that is mainly targeted. For example, in accordance with Balakrishnan and Hansman [29], Towing Aircraft to Runway with a gasoline vehicle (TAR, G) reduces aircraft related pollutants. However, this increases ground support emissions, leading to a total reduction of NO_x during taxiing (10%). This impact is nevertheless, smaller compared to any other individual technology or approach indicated in Figure.

This average estimate is based on calculations for 11 different engines, accounting for different gas turbine architecture and size as shown in the Appendix. The measurement of emissions is considered during the LTO cycle that consists of descent and ascent as shown in Table 1. Descent includes approach from 3,000 feet, taxing/idle, while ascent is taxiing/idle, take-off and climb to 3,000 feet. Although actual operations differ from the LTO cycle, this standardization enables the comparison of different technologies [30]. As such, it is a convenient method for the purpose of this study. More detailed techniques for emission inventories based on actual aircraft operations can be found in [7,30,31].

The emissions reduction effects of each technology have been obtained from Daggett et al. [32] , Brown [33], and Balakrishnan et al. [29,34]. These have been adapted to indicate the classification, type of emission targeted, impact, and mode of operation. Subsequent subsections discuss the respective approaches in further details, to provide a context. More emphasis on Engine Water Injection (EWI) has been made in the latter part.

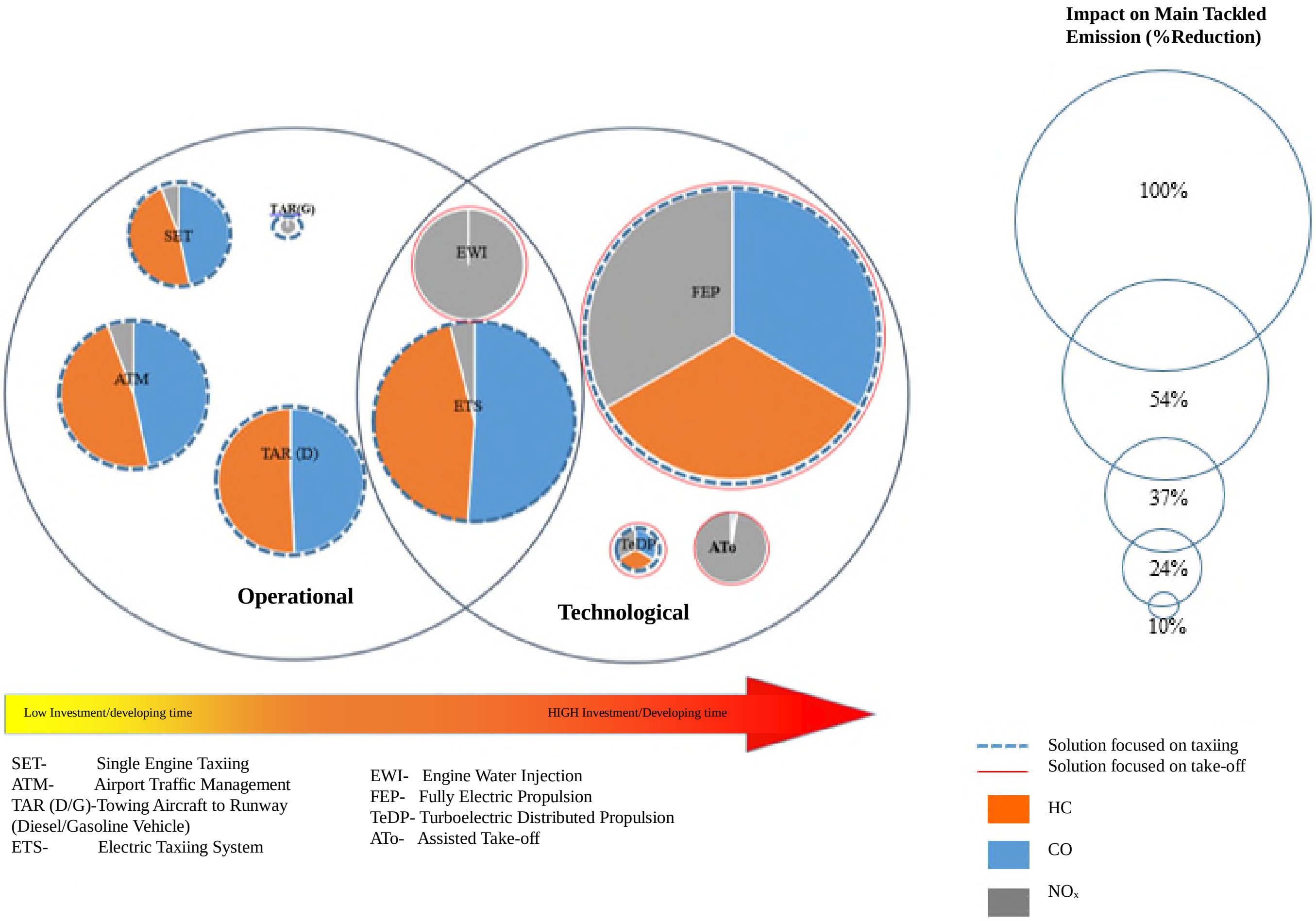

Figure 5 Airport Emissions Mitigating Measures by Type, Impact, development time/cost and pollutant

OPERATIONAL APPROACHES

Single Engine Taxiing (SET) - A world-wide effort in reducing the levels of emission at and around airports is in place. India is one of the countries with the highest growth in air transport demand, with about 25% growth in 2015 [35]. Such growth has brought about SET operation, as encouraged by the civil aviation authority, to reduce emissions, fuel burn and power output [36]. SET consists of using only one engine from pushback to runway approach. Studies suggest that implementation of SET can potentially reduce 25% - 40% of taxi-out fuel burn [34]. During taxiing since the engines operate on low power settings, the primary pollutant emissions are CO and HC (Figs.3 and 4), therefore SET is well suited to target reduction in these specific emissions. The Heathrow airport management plan for emissions reduction is also encouraging airlines to turn-off one or more engines during taxiing, as well as an investment in infrastructure to reduce the use of APU's whilst the aircraft is at the gate [37].

Airport Traffic Management (ATM)- ATM is an avenue for reducing gaseous emissions investigated in Torres and Chaptal [1] and Balakrishnan and Deonandan [34] focused on reducing queues at the runway. The latter study shows a reduction in taxi-out emissions of up to 60% by correctly managing queues, and dispatching one aircraft at a time directly from the gate to the runway. This approach, although attractive, is restricted by the airport throughput and could result in increased overall delays. The Single European Sky (SES) and Airways [38] are initiatives that consist of optimising routes and networks. Flight inefficiencies in Europe dropped from 5.42% (2009) to 4.9% (2014), and the ultimate goal is for the pilots to fly in straight lines between destinations to minimise flight time and fuel consumption [39]. Flight trajectory optimisation measures are intended to reduce aircraft emissions during flight but do little to mitigate airport-related emissions.

Towing Aircraft to Runway (TAR) Taxibot [40] is a towing vehicle controlled and operated by the pilot from the cockpit. Taxibot guides the aircraft to the departing runway while the engines are turned off and is subsequently driven back to the gate by a safety driver. The use of Taxibot or other towing vehicles is restricted to the landing gear loads and cycles, as they are currently not designed for long duration, high-speed towing [34]. Balakrishnan and Deonandan [34] also covers dispatch towing. The study claims that certain pollutants can, in fact, increase using the towing truck, depending on the engine type and hence fuel type utilised in running the vehicle. The use of diesel fuel is suggested to increase NO_x emissions while gasoline fuel comparatively produces more CO. The ICAO Airport Air Quality Manual [30] also comments on this issue suggesting that NO_x emissions from a Diesel aircraft handling vehicle are 5 times higher than for a gasoline one, and CO emissions are 75 times lower. Nevertheless, they both bring about a reduction in the use of jet fuel and hence CO_2. Efforts are also being made at replacing ground support vehicles from internal combustion engines to hybrid or electric vehicles [41].

TECHNOLOGICAL APPROACHES

Assisted Take-Off (ATo)- In 2012 Airbus introduced a concept that promises to be more environmentally friendly through ATo [42]. This idea dubbed “Eco-Climb” is a part of their “Smarter Skies” initiative for 2050 and beyond. ATo includes an electrically driven platform that propels the aircraft out of the airport, removing the need for aircraft propulsion at take-off. ATo would considerably reduce emissions at the take-off roll. The impact of this technology shown in Fig. 5 is calculated by replacing the levels of emissions at take-off – from full power setting (100%) to idling (7%), and subsequently comparing the emissions to the normal LTO cycle. For the implementation of this technology, the operations, infrastructure and design of both aircraft and airports would have to change considerably.

Turbo Electric Distributed Propulsion (TeDP)- The turboelectric distributed propulsion system has been proposed by NASA in conjunction with several collaborations with universities [33,43,44]. The NASA N3-X concept of Turbo-electric Distributed Propulsion (TeDP) on a Blended Wing Body (BWB) airframe involves a low drag shaped aircraft propelled by electric fans powered by the electricity generated by a gas turbine. The fuel burn benefits from this concept come from the higher By-Pass Ratio (BPR) of the electric fans, which produce a higher propulsive efficiency as well as from the boundary layer ingestion which reduces the overall drag [33]. These benefits, however, are counteracted by the weight of the components and inefficiencies of the system. The net impact, evaluated by Brown [33] could translate into a 10% fuel saving. Other challenges of the technology include the positioning of the electric engines, cooling of the superconductors and weight of the components that have been evaluated and presented in Gibson et al. [45] for a conceptual subsonic passenger aircraft. According to NASA, electric distributive propulsion will be the future of flight but we are still a long way away from that [46]. TeDP is accounted for in Fig. 5, taking into consideration a 10% reduction in emissions throughout the LTO cycle and for all the pollutants under consideration (CO, HC, NO_x) representative of the overall fuel saving.

Figure 6 TeDP on a blended wing body airframe [47]

Fully Electric Propulsion (FEP) -The first fully electric-solar powered aircraft – Solar Impulse landed at Dubai International Airport on the 26th of July, 2016, completing the first ever round-the-world, zero-emission flight [48]. Although this solar-powered solution demonstrated in the experimental vehicle (Fig. 7) is attractive in eliminating aircraft emissions, the technological challenges to achieve this on a large scale for international air travel are considerable.

Figure 7. Solar Impulse concept aircraft: [49]

In Fig 5, FEP is represented as the biggest pie chart and it is divided equally into three parts, indicating that it has the biggest impact of all the technologies and it would significantly reduce all the respective pollutants.

Moore [50] evaluates different solutions for distributive propulsive aircraft and mentions the technological challenges associated with them. These challenges include battery development, and weight (estimated to be 25% of the aircraft weight) system reliability, superconductor technology improvement and propulsion integration.

Use of Alternative Fuels- The use of alternative fuels to reduce emissions is being evaluated all around the world [9,51–53]. Kivits et al. [53] conclude that the use of alternative fuels like liquid hydrogen, although promising, is still a distant idea. To achieve this practically, a considerable change in infrastructure would be needed, from airports (storage of the LH_2, vehicles to supply it, extra energy required to keep it at a low temperature etc.) to the airlines, and aircraft design. Allen [51] estimates the increase in an airport facility to be able to do this, and the amount of electricity required, which would have to come from a Carbon-free source. The study also highlights the changes that aircraft would have to undertake to implement this technology. LH_2 has a lower volume power density than current hydrocarbon fuels, meaning that for the same aircraft to fly the same long-haul mission, the fuel tanks would have to be considerably larger, or external tanks would have to be fitted on the aircraft.

The use of Biofuels has been widely used by several airlines for test purposes or on specific routes. In 2008 Air New Zealand successfully completed the first flight powered by a 50-50 mix of kerosene and a second-generation biofuel. Following this, KLM flew Amsterdam to Paris in 2011 with a fuel based on cooking oil. Lufthansa has operated a Frankfurt to Berlin route using a 10% blend based on Sugarcane. Although "drop-in" biofuels have the potential of reducing emissions by up to 80%, this reduction happens mostly at the time of manufacture of the fuel and not during the flight or LTO cycle [36].

TECHNOLOGICAL/OPERATIONAL APPROACHES

Electric Taxiing Systems (ETS)- A study on efficient taxiing systems presented in Re [54], highlights the potential emissions reduction at the airport during taxiing. Examples of ETS includes that of Wheeltug [55] that involves the use of a small electric motor installed at the nose landing gear and powered by the APU. This also eliminates the use of the engines during taxing as well as the need for a towing/tug vehicle or any ground support equipment. A similar approach is also implemented by MagnetMotor [56] currently involving the use of permanent magnet electric wheel drives on the rims, also in the main landing gear

A competing solution developed by Honeywell and Safran [57] and is referred to as the Electric Green Taxiing System (EGTS) has received special interest from EasyJet, that has been involved in exploratory trials. The airline claims that 4% of their annual fuel consumption comes from ground operations, accounting for a travel of 3.5 million miles a year [58]. The system currently involves not only using the APU to power the electric motors at the wheels but using regenerative braking at the landing to store the power into batteries. Galea et al. [59] propose a conceptual design for a wheel actuator that can be used in any of these applications and estimate a 4-5% reduction in fuel burning and carbon emissions.

The implementation of ETS would involve operational changes, like the redundancy of towing vehicles, and the re-positioning of fire crews at the airport, which at the moment are close to the main buildings where the engines are turned on [54]. Another challenge is the engine warm up time that can be as long as 5 minutes [29]. In conventional taxiing, this requirement is fulfilled within the taxiing period, however, if any of these measures were implemented they would mainly be beneficial for operations where taxing times are normally above the engine warm up time.

The impact of ETS was evaluated in this review based on the LTO cycle, by reducing the idling time from 26 to 5 minutes and comparing the total emissions to that of a standard LTO operation. It is important to reiterate that these measures that mainly target taxiing would only have a significant impact on CO and HC pollutants that are more dominant in low power aircraft flight phases like idle or taxiing.

Despite the efforts to reduce emissions based on better operation, better design, new technologies, and more stringent regulations, not one of these solutions on their own would be enough to keep emissions at an acceptable level if the demand keeps growing at the rate foreseen, and considering the long development and certification times associated with the aviation industry [9,15].

Jet Engine Water Injection (EWI)-Engine Water injection provides a way of achieving reductions in emissions, especially NO_x. The studies reported in references [21,60] suggest that if 2% of the total engine mass flow is injected as water into the compressor, the NOx emissions can be potentially reduced by the order of 47%. The implementation of EWI does not demand or necessitate the significant changes in infrastructure or hardware that other technologies may require. Decreasing NO_x was not the initial aim of water injection; six years after the first Whittle turbojet engine flew, Wilcox and Trout [61] conducted experiments on gas turbine performance with water injection for thrust augmentation. The outcome of the study concluded that the effect is more beneficial at low altitudes, high temperatures and low humidities, mainly for take-off conditions. This method has since been widely studied and applied for over 1,000 industrial gas turbines around the world. A comprehensive review of the injection methods, benefits and types of injection is presented in Bhargava et al. [62–64].

EWI technological challenges are minor compared to solutions like FEP or the use of alternative fuels (hydrogen or bio-fuels). Many alternatives intended for reduction of airport-related contaminants target operations at taxiing. Although these measures are necessary it has been seen that taxi at Heathrow accounts for 21% of air pollutants, while take-off accounts for 46% [4]. Moreover, implementing solutions targeted at taxiing would reduce CO and CO_2 emissions but would have little or no effect on NO_x. Considering that the CAEP regulations are focused on NO_x emissions restrictions, it is fundamental to develop technologies that could reach the goals of ICAO of 60% reduction in NO_x by 2026 (compared to the certification CAEP/6) [27]. Water injection at take-off and climb is therefore suggested to complement other operational and technological approaches. This could further reduce the environmental footprint of aviation: dominant carbon pollutants at taxiing, and dominant NO_x pollutants at take-off and climb.

Water injection for gas turbine engines has been historically applied to the combustor or compressor. The following section provides a review of the different methods and impacts on engine performance based on studies from the open literature.

Combustion Chamber (CC) water injection- When water is injected into the combustion chamber, additional energy is required from the fuel to evaporate the water, increasing the fuel consumption and lowering the thermal efficiency [65]. The amount of water required to achieve a certain amount of NO_x reduction is a lot lower if the water is injected into the combustor rather than into the compressor [32] since gas in the combustion chamber is hotter and thus enhances a more efficient evaporative process than that seen in the compressor. Typical figures are in the order of 80% reduction in NO_x for 1:1 water-to-fuel ratio for CC injection [66].

Bahr and Lyon [66] suggest an expression to relate NO_x abatement to fuel heating value, water and fuel flow rates. The investigation shows an increase in CO with rising levels of water-to-fuel ratio for engines with low-pressure ratio, but a steady production of CO with high-pressure ratio compressors; suggesting that modern engines with higher pressure ratios will have more favourable combustion conditions with water injection. The production of CO depends on the efficiency of the combustor, as mentioned previously. Bahr et al. [66] indicate that this value decreases by 0.1% when water is injected into the CC.

Findings of Roumeliotis and Mathioudakis [67] agree with Bahr and Lyon [66] in that the potential of NO_x reduction by injecting water into the combustion chamber has the drawback of a marked decrease in thermal efficiency. Though CC water injection has shown to be more effective at reducing NO_x emissions, there are other technological challenges associated with injecting water into this part of the engine. Daggett et al.[21] indicate some of the historical problems in the early Boeing 747 aircraft powered by Pratt and Whitney JT9D engines. Some of this included non-uniform distribution of water resulted in poor temperature distribution in the HP turbine (injection prior to combustor). Thermal stressing on HP turbine due to sudden introduction of cool water that impinged on hot metal surfaces was also reported as a potential problem [68,69]. Spraying water in the combustor proved even better with steam however only practical for the stationary engines due to the relatively large volume of water needed and steam generating requirements[70].

Compressor Water Injection-When water is injected into the compressor typically at hot and dry ambient conditions, it reduces the air temperature, increasing mass flow, thereby reducing the work required by the turbine to drive the compressor in order to generate thrust or shaft power. Utamura [71] concludes that this reduction in compressor work contributes to a rise in cycle thermal efficiency. This increase in thermal efficiency for stationary gas turbine engines could be achieved at constant power output operation, as well as augmented power operation. The latter involves maintaining the firing temperature or heat input. Cumpsty [72] notes that cycle efficiency depends on the ratio of TIT to Compressor Inlet Temperature (CIT), and that reducing CIT has the same effect of increased efficiency as rising TIT, especially for high-pressure ratio engines.

Water injection consists of two approaches for which the impact and classification are determined by the thermodynamic state of the ambient air. One approach is referred to as inlet fogging/misting which involves the addition of sufficient amount of water at the intake of the engine, so as to cool and saturate (or achieve 100% relative humidity) the inlet air. The other approach is known as wet compression or over spray. The main objective of the latter is to allow for continuous evaporation of water droplets through the compressor. This permits a bigger drop in the compressor outlet temperature due to the intercooling effect, thereby tending towards isothermal compression [70,71]. This method is widely used in industrial gas turbine applications in predominantly hot and dry climates when the demand for energy increases partly due to increased use of air-conditioning. The P-V and T-S diagrams for wet compression are shown in Fig. 8. The points i, wi, s, and n corresponds to isothermal, water injection, isentropic and polytropic process respectively.

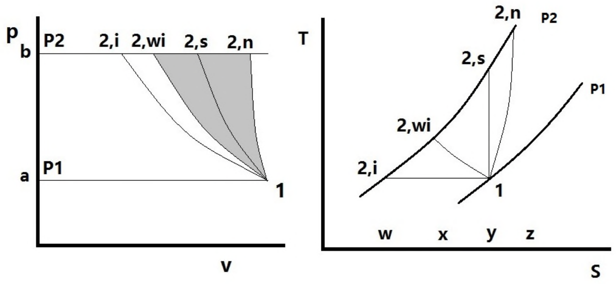

Figure 8 P-V and T-S diagram for wet compression [73,74]

The work corresponding to dry polytropic compression can be calculated from the area 1-2n-b-a-1 on the P-V diagram. The compressor exit entropy and temperature of the gas would be that corresponding to point z, 2,n on the T-S diagram. For an isothermal compression process to take place between P_1 and P_2, the temperature would remain the same (1-2i) and the gas entropy would decrease to w (although in reality, no process can occur with a reduction in entropy, so the overall entropy of the system would indeed increase, but would be comparatively less). The work required for this operation (PV diagram) would be 1-2i-b-a-1. The wet compression process is benefited from a negative heat transfer (from the air to the water droplets), and would lie between the polytropic and isothermal compression. The compression work would be 1-2wi-b-a-1, and the entropy of the gas would decrease to x, as compared to the polytropic case. The difference in compressor delivery temperature is 2n – 2wi, and the difference in compressor work would be the grey area 1-2wi-n2-1 on the PV diagram. Note that the diagrams are representative of a process and are not to scale.

Inter-stage high fogging has been investigated by several authors including Wang and Khan [75], Roumeliotis and Mathioudakis [76], Wang et al. [77] Bagnolli [78] and Sun [74]. The main advantage of injecting between the stages and not just at the entrance of the compressor is the insensitiveness to ambient conditions and ease of control that could be achieved. However, the effectiveness is less pronounced when water is injected into the HPC as compared to LPC. Daggett et al. [21] have reported that a double reduction in SFC can be achieved when injecting into the LPC, as well as a further 3% reduction in NO_x and TIT compared to HPC injection.

Water droplet diameter and residence time are amongst the most important variables dominating evaporation time within the compressor [79]. Reducing the droplet residence time in the compressor by injecting the water as early as possible is of great importance as this ensures that the water is completely evaporated at the end of the compression process, and will reduce the possibilities for blade impact and blade erosion. White [80] suggests the use of droplet diameters below 5 μm to ensure that they follow the flow path, as well as avoid them being centrifuged towards the compressor casing, or impacting on the blades.

Low-pressure compressor (LPC) water injection poses the biggest overall advantages. Utamura et al. [71], Wang et al. [77], Roumeliotis and Mathioudakis [76] and Balepin et al. [81], agree that the most effective location for water injection is at the inlet of the LPC. The main advantage of injecting water into the compressor is the reduction in compressor exit temperature (CET) that ensures a lower flame temperature, which reduces the amount of NO_x. The reduced TIT also causes an extension in the creep life of the turbine, which translates into potential maintenance costs savings.

The polytropic coefficient of wet compression differs from the dry case. The ideal compression will no longer be adiabatic but will be affected by heat transfer to and from the water droplets, approaching a curve that will lie between the isothermal and adiabatic processes [80,82] as shown in Fig. 8. When water injection is applied to maintain the same thrust, at reduced throttle setting, the fuel flow is reduced, decreasing the specific fuel consumption (SFC) [32]. Burning less fuel will have an effect in reducing $CO_{2,}$ at a level proportional to the SFC decrease (4%).

Specialists from engine and aircraft manufacturing companies (Rolls-Royce, Pratt & Whitney, Boeing, NASA) commented on the findings in Daggett et al. [21] that is also available in this study. The comments outline that the water injection maintenance issues presented on the early Boeing 747 & 707 could easily be overcome by today’s techniques and technologies. The benefit of reducing TIT is emphasised, suggesting that such reductions (around 220K) could double the life of the hot components of the engine. Askeland et al. [83] show the impact of temperature on rupture life due to creep, also showing that a very small change in temperature can have a significant effect on hot component life. Daggett [68] estimate that a gas turbine could have its life increased by 46% if water injection is implemented. Cumpsty [72] suggests that turbine blade creep life could be doubled for every 10K drop in temperature.

One of the biggest drawbacks of this approach is the installation on the aircraft and the additional weight of water, tanks and delivery system. Daggett [68] evaluates an increase in weight of about 1540kg for LPC water injection. According to the FAA [84] this could translate to a reduced payload between 13 to 18 passengers depending on their weight and luggage, for a 747-400 aircraft (5% of the passenger capacity [85]).

CONCLUSION

This review has highlighted the existing and predicted trends of approaches/technologies focused on reducing aircraft-related airport emissions. These approaches have been discussed, alongside their merits and the main pollutant tackled. They have been classified as operational, technological or combination of both.

The promise of engine water injection in the compressor when applied to attain the same required net thrust, is very clear. This approach addresses mainly NO_x emissions reduction and to a smaller extent CO_2 emissions. Of the approaches investigated, it is the most promising in terms of NO_x reduction and more ready to be implemented to current infrastructure when compared to the other alternatives evaluated.

The significant reductions in NO_x emissions that can be offered by EWI are particularly timely, given that incoming designs of aero-engines have transonic compressors, which achieve greater pressure ratios per stage and hence higher overall pressure ratios. Higher design overall pressure ratios are accompanied with higher flame temperatures and NO_x emissions, despite the thermal efficiency or SFC improvement.

The gains from the potential life extension of the hot component and reduced SFC are likely to outweigh the cost of demineralised water plus the reduced earnings from fewer passengers. In addition, the airline can take the advantage of the increased earnings/competitiveness from the additional cabin space. The technical confrontations faced by the early onboard water injection systems can be more conveniently address when compared to the constraints of other approaches. This study, more importantly, provides the justification of why compressor water injection needs to be reconsidered: in view of the growth in civil aviation and environmental implications and the promise in relation to other approaches.

NOMENCLATURE

ACRAE	Advisory Council for Aviation Research and Innovation in Europe
APU	Auxiliary Power Unit
ATM	Airport Traffic Management
ATo	Assisted Take-off
C	Carbon
CAEP	Committee on Aviation Environmental Protection
CC	Combustion Chamber
CIT	Compressor Inlet Temperature
CO	Carbon Monoxide
CO_2	Carbon Dioxide
EEA	European Environmental Agency
ETS	Electric Taxiing System
EU	European Union

EWI	Engine Water Injection
FAA	Federal Aviation Authority
FEP	Full Electric Propulsion
GHG	Green House Gases
GSE	Ground Support Equipment
HC	Hydrocarbons
HPC	High-Pressure Compressor
IATA	International Air Transport Association
ICAO	International Civil Aviation Authority
LPC	Low-Pressure Compressor
LTO	Landing and Take-Off Cycle
NASA	National Aeronautics and Space Administration
NO_x	Nitrogen Oxides
O	Oxygen
P	Pressure
SET	Single Engine Taxiing
SFC	Specific Fuel Consumption
SO_x	Oxides of Sulphur
T	Temperature
TAR	Towing Aircraft to Runway
TeDP	Turboelectric Distributed Propulsion
TIT	Turbine Inlet Temperature
UHC	Unburned Hydrocarbons
UK	United Kingdom
USD	United States Dollars

Subscripts

1	Inlet
2	Outlet
i	Isothermal/gas species dimension index
j	LTO Flight phase dimension index
k	Mitigating measure dimension index
wi	Water Injection
s	Isentropic
n	Polytropic

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APPENDIX

For the elaboration of Fig.5, the ICAO emissions certificate for each engine was obtained and the inventory of emissions per LTO stage and pollutant was computed by multiplying Time in Mode (TIM) of the engine by the Fuel Flow (FF) and the corresponding EI (Emission Index) as shown in equation [1]. Here “i” is a dimension corresponding to the gas species (NO_x, CO, HC) and “j” to the LTO flight cycle phase (Take-off, taxi, approach, climb-out).

$$Emission_{\,i\,j}(Kg)=TIM_j*FF_j*EI_i \qquad [1]$$

To account for the corresponding theoretical emission reduction for a given technology analyzed, the following equation was applied to obtain a reduced emission inventory.

$$Emission\ Red_{i\,j\,k}(Kg)=TIM_j*FF_j*EI_{REDi,j\,k} \qquad [2]$$

Where the Reduced Emission Index (EI_{REDijk}) corresponds to the Emission Index of a particular gas species at a particular LTO flight phase. This value is then multiplied by the estimated percentage reduction depending on the approach/technology applied (k), This is mathematically expressed as

$$EI_{RED,i\,j\,k}=EI_{i\,j}*(1-\%RED_k) \qquad [3]$$

For example, it is estimated that Engine Water Injection can reduce NOx emissions by 47% at take-off and climb-out, so the reduced Emission Index for NO_x only would be,

$EI,_{NOx,Take\text{-}off,\ red}= EI_{NOxtake\text{-}off}*(1-0.47)$
$EI,_{NOx,climb\text{-}out,\ red}= EI_{NOX,climb\text{-}out}*(1-0.47)$
$EI_{NOx,taxi}$=Unchanged
$EI_{NOx,approach}$=Unchanged

Subsequently, the individual levels of emissions for the whole LTO cycle per pollutant were added to obtain an LTO inventory as a function of pollutant and engine type. The comparison of all the different technologies, applied to the 11 engine types gave an overall potential impact that each technology could have in reducing the LTO contributions to airport gaseous emissions for each gas species.

The details of the engines used for the Figure can be found in the table below. These are representative of old and new engines, with different architecture and specifications.

Engine	Take-off Thrust (KN)	Pressure Ratio	Spools
GE-CF6-50E	230.00	28.44	2
CFM-56-5B1	133.45	30.20	2
GE90-90B-	419.00	39.85	2
GEnx-1B67/P2	308.70	42.20	2
RR Trent772	315.90	35.79	3
RR RB211-524H-T	264.40	34.00	3
Trent XWB-79	355.20	38.80	3
Trent1000-A	310.80	41.00	3
Trent 970	334.70	38.97	3
PW JT9D-7F	213.50	22.80	2
PW 6124A	105.87	28.00	2

2017-06-30

Case for exploring compressor water injection for airport emission reduction

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ASME

Block Novelo DA, Igie U. (2017) Case for exploring compressor water injection for airport emission reduction. In: ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition: Volume 3: Coal, Biomass and Alternative Fuels; Cycle Innovations; Electric Power; þÿIndustrial and Cogeneration Applications; Organic Rankine Cycle Power
2017, Charlotte, North Carolina, USA

http://dx.doi.org/10.1115/GT2017-64780