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WATER INJECTION ON AIRCRAFT ENGINES: A PERFORMANCE, EMISSIONS AND ECONOMIC STUDY

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ABSTRACT

Although aviation based emissions are not the major sources of atmospheric pollution, their impact around the airport vicinity and the increase in air transport makes it a concern. Water injection on aircraft engines can reduce NOx emissions around the airports significantly. This has been demonstrated in research study by NASA Glenn Research Center in collaboration with Boeing Company. The aim of this study is to investigate the performance, emissions and economic aspects of water ingestion for medium and high bypass ratio jet engines using Cranfield University in-house gas turbine simulation software.

British Airways was chosen as a representative airline to be used as case study in order to examine the effects of this technology. Performance and emissions models were developed for the most popular aircraft of the fleet, along with their engines. The simulations were focused on the take-off phase of the aircraft, injecting water in the low pressure compressor (LPC) and the combustor, for different water-to-air ratios. The results were optimized in terms of fuel burn and verified against the respective results from the NASA study [1]. Finally, an economic model was developed in order to evaluate the monetary impact of these systems, from the point of view of an airliner with a specific number of aircraft in their fleet.

The main outcomes of this study show that LPC water injection can provide more than 10% take-off thrust augmentation in a standard day when in hot days it can exceed 25%. Alternatively, the specific fuel consumption at take-off can reach a 10% reduction, for a fixed take-off thrust level. On the other hand, combustor water injection penalizes the engine performance in all cases.

Additionally, depending on the point of injection and the water to air ratio, NOx emissions reduction ranges between 25%-85%.

Finally, for the case study examined here, the value for the annual monetary benefit due to water injection can reach 599,654£, without taking into account the airport emission based fees. An investment of such sort could present a dynamic payback period of 7.5 years, assuming constant market interest of 8% and 10 years operational life of the equipment.

NOMENCLATURE

CO_2	Carbon Dioxides
EINOx	Emissions Index for NOx
HPC	High Pressure Compressor
i	Market Interest
LPC	Low Pressure Compressor
N	Life of Equipment
NOx	Oxides of Nitrogen
T	Total Temperature
TET	Turbine Entry Temperature
t	Time
TO	Take-Off
WAR	Water to Air Ratio

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1. INTRODUCTION

The last 25 years there has been a dramatic increase in air travel demand all over the world. Therefore the development of more efficient and environmental friendly aircraft became mandatory.

Several technologies have been developed towards that direction, one of which is the "wet low emissions technology". This is a method commonly used in industrial gas turbines in order to reduce the gaseous pollutant emissions and enhance the engine performance. This study examines the applicability of this technology on aircraft applications.

2. EVAPORATIVE INTERCOOLING

A common method used to enhance engine performance was to cool down the air entering a compressor. One of the ways to reduce the temperature of the air is by evaporating water. Introducing misted water at the inlet of the engine can reduce temperature T1. The very fine droplets of water are absorbing energy from the surrounding air and change phase while the air temperature is dropping. The extent of reduction depends on the ability of the air to absorb water. The maximum temperature drop is obtained when the air is fully saturated. Above that point, water injection has no effect on inlet temperature T1.
A simple analytical approach to evaluate the performance of this advanced cycle is presented in the next section [1], [2], [3].

3. WET COMPRESSION

The effect of high ambient temperature on gas turbine performance can be illustrated on the T-S diagram presented below. Increase in ambient temperature will move the initial point from 1 to 1′. Assuming that the cycle will operate between isobars 2-3 and 1-4 and the same turbine entry temperature T3, it can be clearly seen that temperature T2′ and as a consequence compression work will increase while turbine work will remain constant. The increase of T2 is larger than that of T1. The result is a reduction of the useful work produced by the cycle. The exact opposite way shows the effect of decreasing the ambient temperature and the positive effects on engine performance.

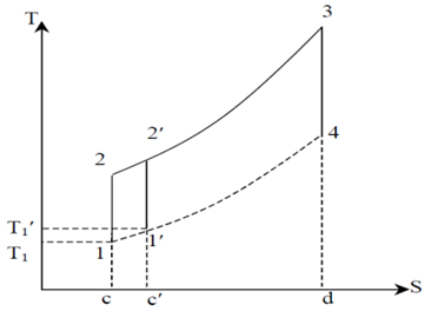

Figure 1 Effect of ambient temperature on the compression process [4].

The case of spraying water over the fully saturated point is referred as overspray and the compression process as wet compression. In that case, the extra amount of water changes phase during the compression process by absorbing the heat produced and reduces the compressor's outlet temperature. This effect is illustrated in Figure 2.

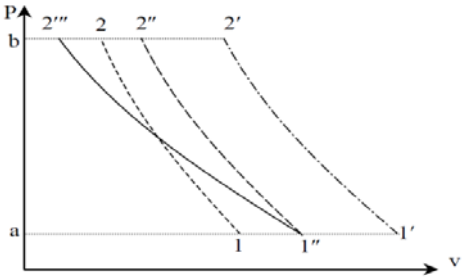

Figure 2 Effect of ambient temperature and overspray on the compression process [4].

The path 1-2 shows the compression process in ISA conditions. Increasing the ambient temperature to T1′, for the same pressure ratio, the route becomes

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1′-2′. Using water injection without overspray we can reduce ambient temperature to T1′′ and the compression process route becomes 1′′-2′′.

In wet compression, a part of the sprayed water is used to saturate the air at the inlet of the compressor and another part is used to absorb heat during compression process. The outlet temperature of the compressor in that case will be T2′′′ < T2′′ and the path that the gas follows will become 1′′-2′′′ (full line).

By the above simple approach we can summarize the basic effects that wet compression can achieve. These effects are presented below:

1. Increase air density.
2. Reduction of compression work.
3. Augmentation in power or thrust.

4. WET LOW NOx EMISSIONS

The increasing demand for power and thrust as well as high cycle efficiency and low specific fuel consumption forced engineers to design gas turbines with the highest pressure ratio possible. High pressure ratio also requires a high combustion temperature.

The generation of oxides of nitrogen (NOx) strongly depends on temperature. At high temperatures nitrogen oxidizes in the air and the oxidation rate increases rapidly with temperature (see Figure 3).

A small amount of water injected to the compressor or the combustor can significantly drop the NOx emissions while the combustion temperature will slightly drop [5].

Water injection systems are very effective regarding the reduction of NOx emissions. Considering that emissions have become an increasingly important consideration in the design of commercial aircraft and engines, water injection systems could become an attractive option for emission reduction technology.

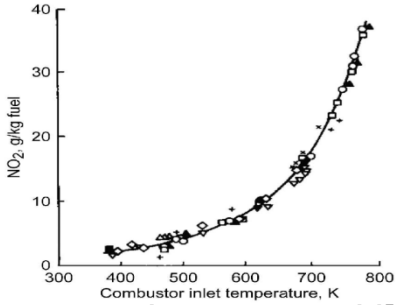

Figure 3 NOx increases rapidly as combustor inlet temperature increases [5].

5. WATER INJECTION SYSTEMS

5.1. ENGINE INLET WATER INJECTION

Engine inlet fogging is a common technic applied successfully on industrial gas turbines for many years. Applying a respective technic on aero engines presents several differences. Figure 4 demonstrates the case of water injection at the inlet of a typical turbofan engine.

It is known that the fan is the most demanding component of a high bypass turbofan engine in terms of power. Evaporating water in front of the fan will decrease the inlet temperature and as a consequence the fan work. Because one of the main aims is the reduction in NOx emissions, portion of the water mist has to pass through the engine core.

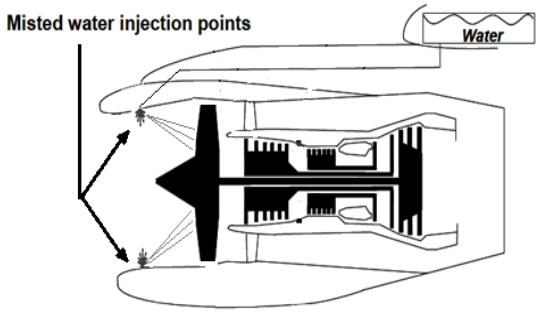

Figure 4 Engine inlet water injection

The problem faced in this case is the large amount of water that passes to the bypass duct and rejected without any benefit. The waste of water is going to be very

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large because of the high bypass ratio and also because the droplets are centrifuged by the fan to the bypass duct. This loss might supersede the gain that the reduction of fan work can offer.

5.2. LPC & HPC WATER INJECTION

A water misting system with injection before the low and high pressure compressors is presented in Figure 5. The air bleed from the high pressure compressor that is used to atomize the water through the nozzles can also be seen in the same figure [5].

The location that water is introduced into the engine, the amount and state of the water (vapour or liquid) and the ambient conditions, can have different impacts at the operating line of each of the compressors. For example, water injection just upstream of the combustor will result in the compressor moving towards the surge line. Injecting water into the inlet of the low pressure compressor will move the high pressure compressor operating line towards the surge line and the low pressure compressor away from it [6].

Analysing the impacts in operation, the engine could be redesigned to operate with these particular surge margins. The redesigned compressor's performance and weight impact could then be taken into account for an overall aircraft performance.

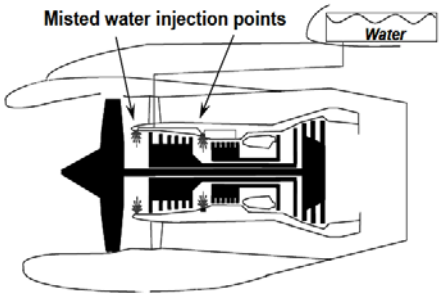

Figure 5 Water injection before the low and high pressure compressors [5].

5.3. COMBUSTOR WATER INJECTION

In case that water is injected directly into the combustor, the arrangement that would lead to acceptable temperature distribution and pattern factors is the one presented below.

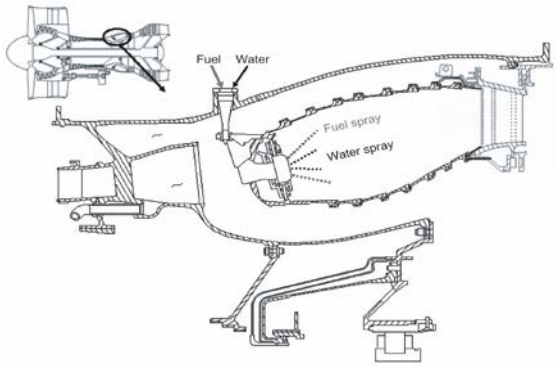

Figure 6 Water injection directly into the combustor [7].

Atomizing together fuel and water through a dual fuel/water nozzle, water and temperature distribution could be controlled and maintained to a desirable level. Also, there was a reduction in the amount of water because direct injection used water more efficiently [7]. This system is well proven and can safely be used on aircrafts.

6. GENERAL METHODOLOGY

This study concerns all airlines which operate missions that involve take-off in ambient temperature higher than 0°C. Especially for airlines operating in warm climates, the application offers a great potential benefit. The benefit maximizes when the system is on short or medium range aircraft because it is directly related to the number of take-offs and the extra weight that has to be carried.

Initially, there was the choice of the airline which will be used as representative and then, the investigation and choice of the most popular aircraft types in the fleet. The four types of engines investigated in this study combined with the ones from NASA cover almost

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all major engine manufacturers and engine types available today on civil aviation (high or ultra-high bypass ratio turbofan engines, 2-spool or 3-spool configurations).

The airline used as a representative example for this study was British Airways. The only data used were the types and numbers of the most popular aircraft in their fleet. That means that any airline using the same aircraft types could be representative. The only difference will appear in the economic model where the number of aircraft affects the results.

The aircraft types chosen were the Boeing 747-400, the Airbus A320-200 and the Airbus A380-800, which are used worldwide by many airlines. The first two aircraft types represent nearly 40% of the fleet and they are among the three most popular aircraft within British Airways. The third is a very promising type which represents the latest technology and is expected to have global success.

The engine types chosen were the RB211-524GHT, the CFM56-5B4P and the RR TRENT 970 respectively. The first two types represent the medium bypass ratio turbofan engines and the last the high bypass ratio turbofan engines. As for the engine configurations there is one 2-spool and two 3-spool engine configurations. These choices provided the opportunity to check for differences on performance impact of water injection systems, based on bypass ratio and engine configuration.

7. PERFORMANCE & EMISSIONS RESULTS

A summary of the main results produced by all the above procedures is contained in this section. Initially, performance and emissions simulation results are presented for each engine separately and then a comparison between them based on their configurations and bypass ratios. Finally, there is a reference about the weight impact on aircraft performance.

7.1. LPC WATER INJECTION

The first engine model was based on RB211-524GH engine performance specifications. It represents a typical Medium ByPass Ratio 3-Spool (MBPR-3S) turbofan engine. This is the engine used to study the economic viability of the system. Due to that, there has been an extension in the simulation process for this particular engine. In order to translate the water injection benefit in fuel consumption reduction we had to perform some extra calculations.

The basic calculations for every engine referred to the effect of water injection for several values of WAR at fixed TET and ambient conditions. The chart below demonstrates the effect of water injection in front of the LPC for the take-off condition of the MBPR-3S engine model.

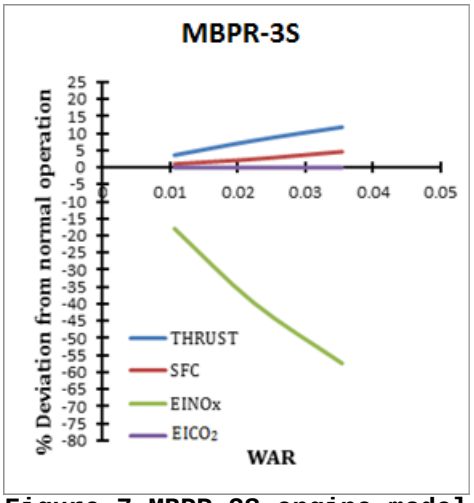

Figure 7 MBPR-3S engine model results for LPC water injection

It can be clearly seen that the thrust is increasing as we increase water injection. The trend of that increase shows that as it moves towards higher WAR the increase in thrust is dropping. Eventually it will reach a level where there will be no more gain in thrust due to water injection.

The SFC is rising as we increase the WAR but its rise is lower than

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that of thrust. However, as we increase the WAR, the SFC presents an opposite trend. As we move to higher WARs the SFC increase gets higher. This fact also supports the statement that after a point water injection cannot offer any performance benefit.

Table 1 MBPR-3S, Example results for LPC water injection

TET K	Thrust N	SFC g/kN*s	EINOx g/kg_{fuel}	WAR %
1600	268929	9.340	14.7	0.0
1600	290064	9.568	8.9	2.24
1600	278635	9.435	12.1	1.06
1600	300695	9.771	6.7	3.54
1500	274956	8.826	10.7	2.24
1400	272759	8.230	9.1	3.56
1380	268579	8.156	8.6	3.56

Table 1 presents some of the results in case the target was to bring the thrust level back to its original value. In that case the SFC decrease would reach 12.6% and the EINOx 41.5%.

The amount of EINOx is decreasing with the increase of WAR. Because our target is to reach the lowest level of emissions, the WAR that is going to be used must be the highest possible. It can be clearly seen that this technology can exceed a 50% reduction in NOx emissions.

The second engine model was based on the RR Trent 970 engine performance specifications. It represents a modern High ByPass Ratio 3-Spool (HBPR-3S) turbofan engine, which already is at a high technological level.

Figure 8 illustrates the LPC water injection impact on engine performance and emissions. It can be clearly seen that it has a powerful effect on NOx emissions, which in the case of 4.4% WAR approach the value of 80% reduction. However, the penalty in performance is also very clear. At each water injection case, SFC increase was much higher than thrust augmentation. Using water injection in this engine can significantly reduce the NOx emissions but not without a penalty in SFC. That means that this might not be an economic viable case study.

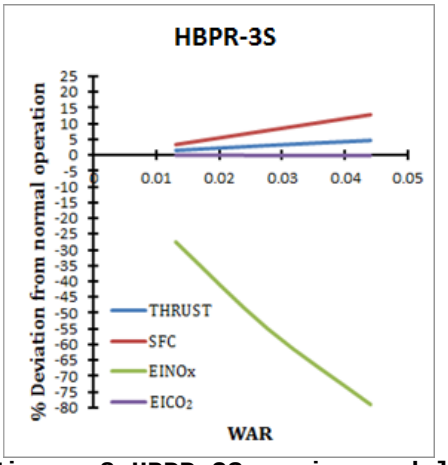

Figure 8 HBPR-3S engine model results for LPC water injection

Besides that, the trends are similar to the previous one. The thrust and SFC are increasing with the increase of water injection and the NOx emissions are decreasing, which is something expected. The only difference is that the trends are closer to linear than in the MBPR-3S case (see Figures 8 and 9).

The third case represents engines with lower thrust class. The model was based on CFM56-5B4/P engine performance specifications. It represents a modern Medium ByPass 2-Spool (MBPR-2S) turbofan engine. Although this wasn't the engine chosen for the economic study, it was the one with the most promising results in terms of performance.

The chart below presents the performance and emissions results for applying water injection in front of the LPC. It is obvious that there is a significant difference on the performance impact compared to the previous engines. At this engine, the thrust augmentation achieved is much higher, when there is also a small benefit in SFC at lower values of WAR.

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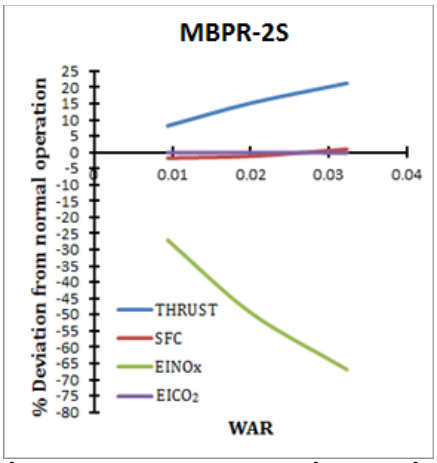

Figure 9 MBPR-2S engine model results for LPC water injection

The drop in EINOx is also remarkable, reaching -66.9% at a WAR of 3.23%. However, the general trend of the curves is similar to all previous cases, fact which provides confidence about the effect of water injection on typical aero engine performance and emissions.

Table 2 MBPR-2S, Example results for LPC water injection

TET K	Thrust N	SFC g/kN*s	EINOx g/kg_{fuel}	WAR %
1490	121718	8.261	33.2	0.0
1490	140327	8.155	16.8	2.01
1490	131796	8.108	24.2	0.94
1490	147739	8.335	11.0	3.23
1320	126086	7.186	22.7	2.40
1305	122675	7.154	24.7	2.33

The case of reduction in TET in order to generate similar thrust with the baseline operation would reduce the SFC about 13.5% which is the best of all cases in terms of performance enhancement (Table 2).

7.2. COMBUSTOR WATER INJECTION

Although LPC water injection was examined for fixed TET, combustor water injection is checked against fixed thrust. This is because in this case there is no thrust boosting capability and the target of the technology is mainly NOx reduction. The results for the 2-spool engine configuration are not presented here deliberately due to the fact that they are similar to those of the 3-spool configuration.

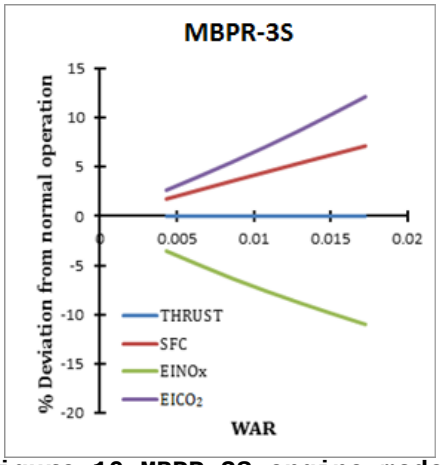

Figure 10 MBPR-3S engine model results for combustor water injection

Observing the Figures 10 and 11, it is obvious that increasing the WAR increases the SFC and as a consequence the $EICO_2$. The EINOx drop however, is not as aggressive as it was in the case of LPC water injection. This is mainly due to the fact that NOx emissions generation strongly depends on combustor inlet temperature, which is not affected in this case.

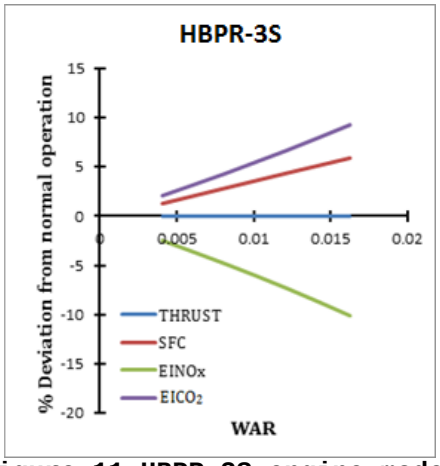

Figure 11 HBPR-3S engine model results for combustor water injection

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7.3. MISSION FUEL BURN ANALYSIS

The weight estimation for the water injection equipment was based on the case of injecting water in front of the LPC.

The weight of the equipment was estimated specifically for the case of MBPR-3S engines installed on Boeing 747-400 series aircraft. The estimation was based on details about the equipment parts from reference [7] and data provided by R-MC Power Recovery Ltd. The table below presents the results from the equipment weight estimation. The reduced weight of the equipment compered to reference [7] is because the water pumps for LPC injection are lighter.

Table 3 Equipment weight estimation results

Equipment	Weight (kg/aircraft)
Water Tanks and Mounting	80
Pump & Motor	40
Control Unit	20
Valves - Sensors - Wiring	50
Pipe Lines & Stabilizers	95
Nozzles	Negligible
Total	285

Data from public domain regarding the maximum take-off weight of a Boeing 747-400 series showed that its value ranges between 396,890kg and 412,775kg. If we consider the lower value of 396,890kg, the weight addition due to the equipment increases the total weight 0.07%. The additional fuel required in order to carry the equipment empty for a 3000nmiles mission was estimated based in the value given in reference [7] and the weight of the equipment. Table 4 contains the fuel and water weights during take-off for the baseline and water injection cases.

Most of the water filled on the aircraft is going to be consumed before lift-off. The rest is going to be consumed at the first 30 seconds of climb. Its weight is going to be approximately 150kg and its performance impact was already taken into account.

Table 4 Water & fuel weight effects

Parameter	Weight (kg)
Fuel required at take-off - water injection	700.4
Fuel required at take-off - baseline	783.7
Total water weight per take-off	1558.4
Fuel penalty for carrying the equipment	41.6
Overall fuel weight benefit per flight	41.7

Another approach could be the reduction in payload or range of the aircraft. Based on reference [7], the total weight increase of 0.07% can result in 0.25% decrease in payload or approximately 0.03% reduction in range. If we consider a medium range mission of 3000nmiles, weight addition would decrease it approximately 9nmiles. If the flights are not range or payload limited the weight addition effect of the empty water injection equipment could be negligible.

8. ECONOMIC ANALYSIS

The economic analysis was conducted under the context of the system's viability study. The aim was to investigate whether these systems can become an attractive option for an airline from an economic point of view. The procedure of the analysis includes an initial estimation of the costs involved and it is performed with constant values ignoring the inflation.

A typical example of a flight cost distribution translated in passenger seats for a civil aircraft is presented in Figure 12. The performance calculations showed that operating the engine with water injection can decrease the fuel

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consumption approximately by 12% relatively to the case without water injection. Assuming similar effects in the above case, a decrease in the fuel cost by 3 passenger seats is expected. If the weight addition to the aircraft is less than that, then the system can provide a positive economic impact. The impact on maintenance and the salaries is not clear and need farther investigation because there are both positive and negative effects that take place. As for the fees and taxes, they are expected to contribute positively due to the reduction in NOx emissions, especially in the future.

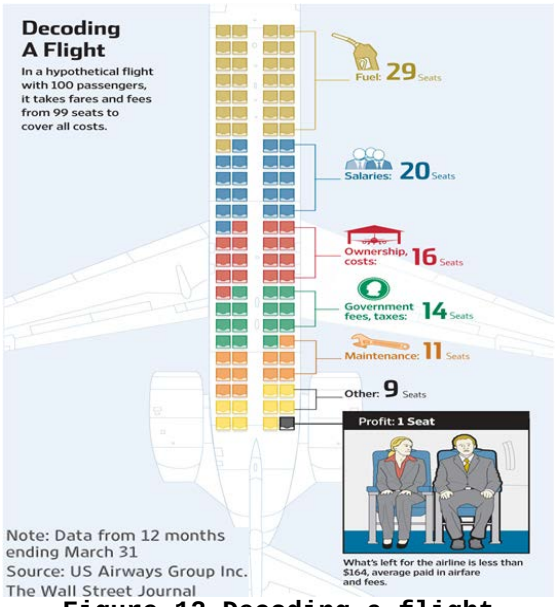

Figure 12 Decoding a flight

The economic analysis was performed by applying two closely related approaches: the simple and the dynamic approach.

Both simple and dynamic analysis performed based on the same basic values. All necessary constant values as well as the input case were set independently of the approach used.

The cost of water injection equipment was determined for the case of Boeing 747-400 series aircraft powered by RB211-524GH engines represented by the engine performance simulation model MBPR-3S. The list for the necessary parts was based on the detailed list for equipment parts described in reference [7].

The table below contain the basic parts that were taken into account. The prices and weights of the equipment parts as well as for the demineralized water were estimated by the author in corporation with R-MC Power Recovery Ltd. A market research followed in order to validate the chosen values.

Table 5 Water injection equipment cost /aircraft

Equipment	Price/Unit (£)	Units	Total Cost (£)
Water Tanks	1,037.5	4	4,150
Pump & Motor	2,500	4	10,000
Control Unit	8,000	1	8,000
Valves - Sensors - Wiring	10,000	1	10,000
Pipe Lines & Stabilizers	5,000	1	5,000
Nozzles	20	80	1,600
Installation Cost (£)	15,000	1	15,000
Total			59,125

Table 6 Constant values used for every aircraft

Annual Operation Cost (£)	2,000
Annual Maintenance Cost (£)	10,000
Life of Equipment (years)	10
Demineralized Water Cost (£/Lit)(including transportation)	0.02
Jet Fuel Price ($/mt)	1,011.3
Time of injection per take off (min/TO)	1.3
Exchange Rate - £ to $	0.62

The necessary constant values used in both simple and dynamic analysis for every aircraft are demonstrated in Table 6. The operation and maintenance costs refer to the water injection equipment independently. There is also a potential reduction in the washing frequency for the engines,

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fact that can reduce the overall maintenance cost but in this study it is excluded. For the demineralized water, the value used was the current price given by R-MC Power Recovery Ltd including the expenses for transporting the water to the aircraft.

An example of the input data for any specific case used in the model is demonstrated in the table below.

Table 7 Economic model input data

Boeing 747-400 powered by four MBPR-3S engines			
Engine Status	**Normal**	**Case 1**	**Case 2**
Number of Aircraft	57		
Number of Engines	4		
Takeoff per day (TO/day)	4		
Days per Year	288		
Water to Air Ratio	0%	3.55%	2.24%
Fuel Flow (kg/s)	2.512	2.245	2.427
Water flow (kg/min)	0	299.7	189.2
Pipe Lines & Stabilizers Weight (kg)	95		
Nozzles/Engine	14		
Installation Cost (£)	15,000		

All the values in Table 7 concern the specific airline and aircraft chosen. The number of take-offs per day is representative for mid-range aircraft with an average flight time of 3 hours. A simple web research showed that aircraft like Boeing 747-400 usually operate 6 days per week, for 48 weeks per year. One month per year is required for overhaul maintenance. Water to air ratio, fuel flow and water flow are data provided by the performance simulation model MBPR-3S. The pipe lines and stabilizers weight was estimated for the specific aircraft. Finally, the installation cost for the equipment varies depending on the aircraft so the value given in the input data refers to this specific case also.

8.1. SIMPLE ANALYSIS

Simple analysis does not take into account the change in the value of money with time. That means that the market interest rate is equal to zero (i=0).

The net present value of the entire life of the equipment is given by the equation:

$$NPV = -C + SV_0 + AB*N \quad (1)$$

The simple payback period is given by the equation:

$$SPB = (C - SV_0)/AB \quad (2)$$

The return on investment is given by the equation:

$$ROI = AB/(C - SV_0) = 1/SPB \quad (3)$$

8.2. DYNAMIC ANALYSIS

Dynamic analysis takes into consideration the change in the value of money with time. An average value of market interest rate has been chosen for this purpose.

The net present value of the entire life of the equipment is given by the equation:

$$NPV = -C + SV_0 + \sum_{t=1}^{N}[AB/(i+1)^t] \quad (4)$$

In our case the annual benefit is considered to be constant every year, so:

$$NPV = -C + SV_0 + AB* \sum_{t=1}^{N}[1/(i+1)^t] \quad (5)$$

and

$$PWF = \sum_{t=1}^{N}[1/(i+1)^t] \quad (6)$$

is the present worth factor.

Finally the net present value is:

$$NPV = -C + SV_0 + AB*PWF \quad (7)$$

Dynamic payback period is the minimum value of time required for

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the net present value to be a non-zero positive quantity. At the limit we have NPV = 0, so:

$$0 = -C + SV_0 + \sum_{t=1}^{DPB}[AB/(i+1)^t] \Rightarrow$$

$$DPB = -\ln[1 - i*(C - SV_0)/AB]/\ln(i+1) \qquad (8)$$

Return on investment is the value of market interest i that makes the net present value of the entire life of the equipment equal to zero:

$$NPV = -C + SV_0 + AB* \sum_{t=1}^{N}[1/(ROI+1)^t] = 0 \qquad (9)$$

Equation (9) can be solved by an iterative process.

8.3. ECONOMIC ANALYSIS RESULTS

Table 8 presents the results of the economic analysis for the case of LPC water injection on MBPR-3S engines installed on Boeing 747-400 series aircraft. Because of all the assumptions and the choice to neglect the impact of the empty equipment weight addition, a 20% penalty factor was taken into account. Even in the worst case of 20% penalty, the annual monetary benefit due to water injection can reach the value of £559,654 and the dynamic payback period 7.5 years. The results demonstrate a high possibility for these systems to become a successful business case for the airline.

Table 8 LPC Water injection system economic analysis

LPC Water Injection		Simple Analysis	Dynamic Analysis
Investment Cost of Water Injection Equipment (£)	**C**	3,340,029	
Annual Cost of Demineralized Water (£)	**C_w**	2,046,668	
Salvage Value of Equipment at the end (t=N)(£)	**SV_N**	436,278	436,278
Present Value of Salvage Value (t=0)(£)	**SV_0**	436,278	202,081
Annual Operation Cost (£)	**C_{op}**	114,000	
Annual Maintenance Cost£)	**C_m**	570,000	
Annual Cost for Fuel Without Water Injection (£)	**C_f**	32,264,977	
Annual Cost for Fuel With Water Injection (£)	**C_{fwi}**	28,834,742	
Market Interest	**i**	0	0.08
Life of Equipment (Years)	**N**	10	10
1/((1+ROI)^t)			4.486
Annual Benefit due to Water Injection (£)	**AB**	699,567	699,567
Net Present Value(£)	**NPV**	4,091,918	0.0
Simple Payback Period (Years)	**SPB**	4.15	
Return on Investment	**ROI**	0.24	0.18
Present Worth Factor	**PWF**		6.71
Dynamic Payback Period (Years)	**DPB**		5.24

Some important observations during the economic analysis pointed out that increasing the number of aircraft that use this technology, the monetary benefit increases. Also, the case of short range aircraft would minimize the actual penalty due to weight addition. Finally, aircraft that operate at the hot regions of the planet would maximize the benefit due to the reduction of fuel consumption.

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9. CONCLUSIONS

This study aimed at the evaluation of water injection systems as a low emissions and economic viable technology for civil aviation.

Based on the results of this study as well as on respective NASA research, some very important conclusions were extracted about the effects of water injection systems on civil aircraft.

Initially, it is important to refer to the system's performance benefits and their consequences. Water injection systems offer thrust boosting capabilities to the aircraft. Applying water injection in front of the LPC can provide easily a 10% thrust augmentation in a standard day when in hot days it can exceed 25%. Thrust boosting can also broaden the range of destinations at airports that have shorter runways.

Alternatively, water injection offers a significant reduction in take-off SFC. For civil aircraft, water injection can reduce the fuel consumption during take-off more than 10%. That directly translates to a potential economic benefit and makes the technology attractive for aircraft operators and airports.

The environmental impact of the technology gathers most of the interest due to its effectiveness as a low NOx emissions technology. The levels of NOx emissions achievable using water injection are impressively low. Depending on the method and amount of water injection, NOx emissions reduction ranges between 25%-85%. In the basic case investigated for LPC water injection, the achieved reduction in NOx emissions was 36%. Finally, having in mind the environment in a global scale, this technology contributes in the reduction of fossil fuels consumption as well as in NOx and CO_2 emissions.

Through the use of simplifications and economic indicators and from the point of view of an airline, these systems proved to be a potentially profitable business case. The value for the annual monetary benefit due to water injection for this case reached £599,654. An investment of such sort could present a dynamic payback period of 7.5 years, if we consider constant market interest 8% and the operational life of the equipment equal to 10 years. The positive economic outcome indicates that the technology could potentially escape the field of scientific research and actually be used on modern civil aviation.

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