

American Society of Mechanical Engineers

GT2017-63440

ASSESSMENT OF THE EFFECT OF ENVIRONMENTAL CONDITIONS ON ROTORCRAFT POLLUTANT EMISSIONS AT MISSION LEVEL

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ABSTRACT

It is anticipated that the contribution of rotorcraft activities to the environmental impact of civil aviation will increase in the forthcoming future. Due to their versatility and robustness, helicopters are often operated in harsh environments with extreme ambient conditions and dusty air. These severe conditions affect not only the engine operation but also the performance of helicopter rotors. This impact is reflected in the fuel burn and pollutants emitted by the helicopter during a mission. The aim of this paper is to introduce an exhaustive methodology to quantify the influence of the environment in the mission fuel consumption and the associated emissions of nitrogen oxides (NO_x). An Emergency Medical Service (EMS) and a Search and Rescue (SAR) mission were used as a case study to simulate the effects of extreme temperatures, high altitude and compressor degradation on a representative Twin-Engine Medium (TEM) weight helicopter, the Sikorsky UH-60A Black Hawk. A simulation tool for helicopter mission performance analysis developed and validated at Cranfield University was employed. This software comprises different modules that enable the analysis of helicopter flight dynamics, powerplant performance and exhaust emissions over a user defined flight path profile. The results obtained show that the environmental effects on mission fuel and emissions are mainly driven by the modification of the engine performance for the particular missions simulated. Fluctuations as high as 12% and 40% in mission fuel and NO_x emissions, respectively, were observed under the environmental conditions simulated in the present study.

NOMENCLATURE

Acronyms

AGL	Above Ground Level
CO_2	Carbon dioxide
DP	Design Point
DZ	Dilution Zone
EI	Emission Index [g/kg fuel]
EMS	Emergency Medical Service
F	Flap vibration mode
FF	Flame Front
GTOW	Gross Take-Off Weight [kg]
HECTOR	Helicopter Omni-disciplinary Research platform
ISA	International Standard Atmosphere
IZ	Intermediate Zone
L	Lag vibration mode
MCP	Maximum Continuous Power
MR	Main Rotor
NO_x	Nitrogen oxides
OD	Off-Design
P	Rotational speed multiple
PR	Pressure Ratio
PZ	Primary Zone
SAR	Search and Rescue
SL	Sea Level
T	Torsion vibration mode
TEM	Twin Engine Medium

TET	Turbine Entry Temperature [K]
TR	Tail Rotor
WGS 84	World Geodetic System dated in 1984

Symbols

A	Main rotor area [m^2]
$C_p = P_{MR} / \rho A (\Omega R)^3$	Power coefficient [-]
$C_t = T_{MR} / \rho A (\Omega R)^2$	Thrust coefficient [-]
P_{MR}	Main rotor Power [W]
R	Main rotor radius [m]
T_{MR}	Main rotor thrust [N]
V	Air velocity [m/s]

Greek

Γ	Mass flow capacity [-]
Δ	Increment [%]
Ω_0	Main rotor rotational speed [rad/s]
η	Isentropic efficiency [-]
ρ	Air density [kg/m^3]
σ	Main rotor solidity [-]
ω	Blade natural frequency [rad/s]

INTRODUCTION

Background

Rotorcraft are able to undertake missions that are impossible for other aircraft, and have found a wide range of applications such as medical evacuation, search and rescue and off-shore oil platforms service. These missions often include operation in harsh environments such as deserts, mountain regions and off-shore areas. These severe environments usually involve atypical atmospheric conditions, which affect significantly the performance of the engine. For example, the extreme temperatures found in a hot desert have a negative impact on the engine power output and efficiency. Flight at high altitudes also reduces the power generated by the engine, even though the efficiency slightly increases. The atmospheric conditions also affect the performance of the helicopter rotor blades [1]. A reduction in air density, due to either a rise in air temperature or flight altitude, will cause an increase in the power required to hover and fly at lower speeds. The opposite effect is seen at higher speeds, where the lower air density translates into a reduced power demand as a result of the reduction in parasitic drag. Another characteristic of these environments is the presence of particles in the air, such as dirt, salt and sand, which can promote deterioration of the engine components due to fouling, erosion and corrosion. Engine deterioration has a detrimental effect on the flow capacity and efficiency of the affected component. Therefore these demanding environmental conditions are expected to affect the fuel consumption and pollutant emissions of the rotorcraft. The

extent by which the environmental footprint of the helicopter is influenced by the ambient conditions is quantified in the present work in order to effectively address in service rotorcraft operation sustainability.

Case Study

Rotorcraft emissions assessment is an arduous task due to the lack of publicly available engine emissions data and the fact that there is no generally accepted methodology for the helicopter emissions calculation. In order to fill this gap, the Swiss Federal Office of Civil Aviation (FOCA), launched the HELEN (HELicopter Engines) project in January 2008 [2]. As an outcome of this project, several empirical functions were developed from experiments conducted on a wide range of helicopters in order to calculate the fuel flow and the Emission Index (EI) of the most standard pollutants. However, this method has a lack on accuracy of $\pm 15\%$ for fuel prediction and an estimated error of a factor of two or more for emissions calculation. Besides, the expressions derived by FOCA are uniquely a function of engine shaft power, which implies that environmental conditions or engine health parameters are not taken into consideration. Therefore the aim of this work is to establish a thorough methodology that enables to quantify the effect of environmental conditions on the performance of a helicopter in terms of fuel consumption and NO_x emissions. In order to predict the fuel consumption and pollutant emissions, the coupled simulation of the helicopter flight dynamics and gas turbine engine operation is required at different control points during the mission. The in-house TURBOMATCH software developed at Cranfield University [3] is used to simulate the engine performance, whilst the in-house HEPHAESTUS tool [4] is employed to predict the pollutant emission rates. These two computational tools are implemented within a third in-house framework called HECTOR [5] that simulates the rotorcraft flight dynamics. The proposed methodology constitutes a stand-alone environment able to simulate the performance of different helicopter platforms at any user defined conditions. Particularly, the effect of extremely hot temperatures, dust particles ingestion and high altitude are investigated in the present analysis. For this purpose two mission roles are considered which are referred to as Emergency Medical Service (EMS) and Search and Rescue (SAR) missions. Under the EMS mission, the conditions of a hot desert have been reproduced to evaluate the effect of high temperature and engine degradation, due to dust ingestion, on the helicopter performance. For the SAR mission, a ‘High & Cold’ scenario was assumed to assess the effect of low temperature and low density air on the rotorcraft operation. The results obtained at the ‘High & Cold’ scenario are benchmarked against the results produced when standard environmental conditions are set over the same mission trajectory. The helicopter platform considered for the analysis is a Twin-Engine Medium (TEM) weight helicopter modelled after the Sikorsky UH-60A Black Hawk powered by two General Electric T700-

GE-700 turboshaft engines. This helicopter is a multi-role rotorcraft designed to operate in hostile environments, such as those considered in this work [6], with extensive data available for validation in the public domain.

Scope of Present Work

The numerical framework employed herein to simulate the performance of the helicopter, HECTOR, has been applied in the past to assess fuel consumption and NO_x emissions at rotorcraft mission level [7], and it has been also employed in the optimization of conventional and regenerative powerplant configurations in terms of rotorcraft operational and environmental performance [8,9]. In addition to this work, several studies have been conducted in the optimization of the helicopter flight path and operational procedures for environmental impact reduction [10,11]. These research activities have been completed assuming standard atmospheric conditions and ‘clean’ engine configurations. Therefore, no allowance has been made so far for the influence of realistic operational conditions on the final helicopter environmental footprint. Thus, the aim of the present study is to fill this existing gap in rotorcraft performance analysis at mission level, by providing some insight on the deviation of helicopter environmental impact from the standard case, when realistic scenarios are considered. To that end, the effects of ambient temperature and flight altitude on helicopter main rotor power demand are shown, together with the effect these parameters and compressor degradation have on engine performance and NO_x production. The time-variations of the parameters of interest, i.e. main rotor power, engine fuel flow and NO_x production rate, are investigated and the total mission results are evaluated.

The analysis conducted in the present work complements the work already developed on the assessment of rotorcraft environmental impact and offers a first estimation of the effect relevance operational conditions have on final helicopter performance and environmental impact.

ROTORCRAFT MODEL DEVELOPMENT

The helicopter flight dynamics are simulated with an in-house rotorcraft comprehensive code named HECTOR (Helicopter Omni-disciplinary Research platform). A more detailed description of HECTOR was reported by Goulos [5], and only the key aspects are summarized here for completeness. This software permits the comprehensive simulation of three-dimensional helicopter missions employing a cost-effective methodology. HECTOR constitutes an integrated tool that comprises the Lagrangian rotor blade modal analysis method [5, 12], a flight path profile analysis based on the World Geodetic System dated in 1984 (WGS 84) [13], a nonlinear trim procedure solving for the aeroelastic behavior of the main rotor [14, 15], the in-house engine performance analysis code

TURBOMATCH first developed by MacMillan [3], and the gas turbine emissions prediction tool HEPHAESTUS created by Celis [4]. This software has been validated and extensively used in previous rotorcraft studies [8, 9]. The HECTOR architecture is shown in Fig. 1.

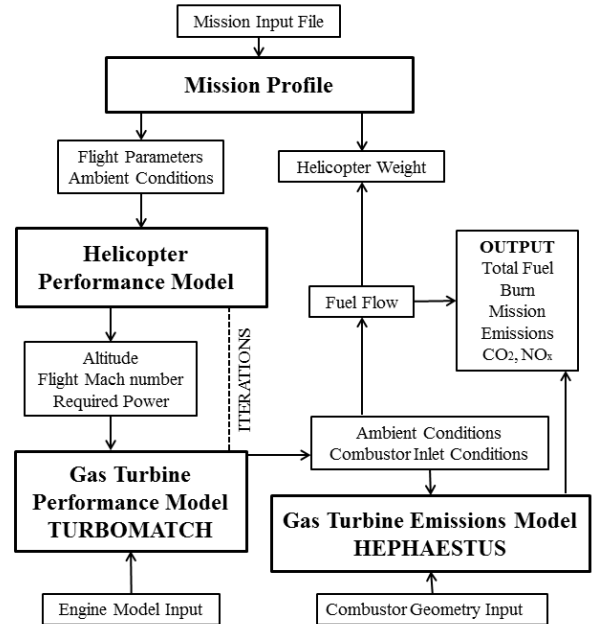


Figure 1 HECTOR architecture scheme [9]

The engine performance simulation code TURBOMATCH has been previously used in several studies to predict the engine performance of different gas turbine engine architectures [16, 17]. TURBOMATCH allows the simulation of Design Point (DP) and Off-Design (OD) performance of any gas turbine configuration and is able to account for the level of degradation of engine compressor and turbine components.

The gaseous emissions are predicted with the in-house tool named HEPHAESTUS. A full description of the code theory and validation is provided by Celis [4], and only the main aspects are included herein for completeness. HEPHAESTUS predicts the pollutant emissions based on the ambient conditions, air conditions at the entry of the combustor, fuel properties, combustor geometry and air flow distribution within the combustor liner. The calculation is based on the stirred reactor concept along with a scheme of simplified chemical reactions that estimate the production of different pollutant species during the fuel combustion in conventional combustor chambers.

Rotorcraft Modeling

The rotorcraft model was developed after the Sikorsky UH-60A Black Hawk helicopter. The UH-60A is a TEM helicopter powered by two General Electric T700-GE-700 turboshaft engines. The main rotorcraft model design

parameters are presented in Table 1. The UH-60A Black Hawk has been extensively studied in the past. Numerical and flight test analyses are documented in the literature [18-20], so further description is omitted.

Table 1 Rotorcraft model design parameters [18]

Empty weight [kg]	5082
Solidity, σ [-]	0.089
Number of blades [-]	4
Blade radius, R [m]	8.178
Blade chord [m]	0.527
Blade airfoils	SC1095 & SC1094 R8
Equivalent blade twist [deg]	18
Nominal rotor speed, Ω_0 [rad/s]	27.01

Rotorcraft Model Validation

The rotorcraft model implemented in HECTOR has been validated against experimental and flight test data available in the public domain. Figure 2 presents the resonance chart calculated for the UH-60A main rotor. The natural frequencies and rotor speed have been normalized with the nominal rotor speed (Ω_0). The solid lines represent the calculated natural frequencies, whilst the discrete points represent the experimental data. The procedure used to obtain the experimental data is described by Hamade *et al* [19]. Overall good agreement between calculated and experimental data is observed for all the natural modes analyzed, with relative errors lower than 5%. An extra natural mode associated with a rigid lead-lag mode is observed which was not reported in the experimental set of data.

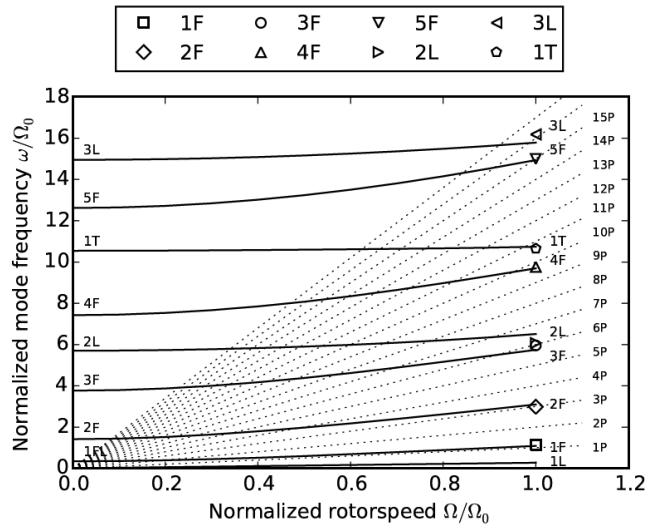


Figure 2 Resonance chart of the UH-60A main rotor

Figure 3 presents the calculated dominant mode shapes for the first nine modes of vibration of the UH-60A main rotor at nominal rotorspeed. Accordingly with Fig. 2, the extra lag mode shape is shown.

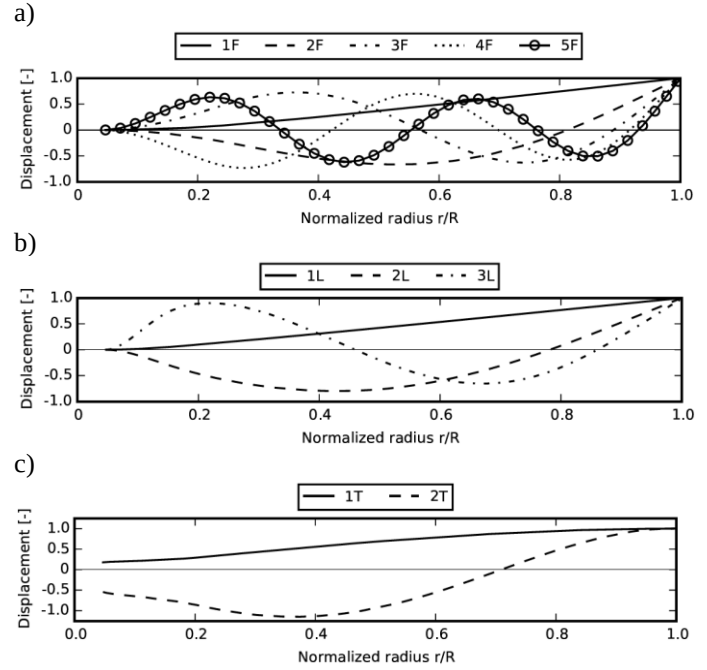


Figure 3 Shape of the main rotor vibration modes: (a) Flap mode, (b) Lag mode, (c) Torsion mode

Figure 4 presents the variation of the power coefficient (C_p) of main rotor (MR), tail rotor (TR), and total power coefficient with the advance ratio ($V/\Omega R$) for a given blade loading ($C_t/\sigma=0.08$). The power requirements estimated with HECTOR exhibits good correlation with the set of flight test data documented by Bousman *et al* [20]. The largest discrepancies are observed at high speed for both, main and tail rotor. This can be attributed to the uncertainty of the estimated fuselage aerodynamic maps used in HECTOR, which can lead to a different flight trim state and thus to a different power requirement. However, the maximum advance ratio simulated in the case studies is lower than 0.3 (66 m/s) and therefore these discrepancies have no effect on the overall mission result.

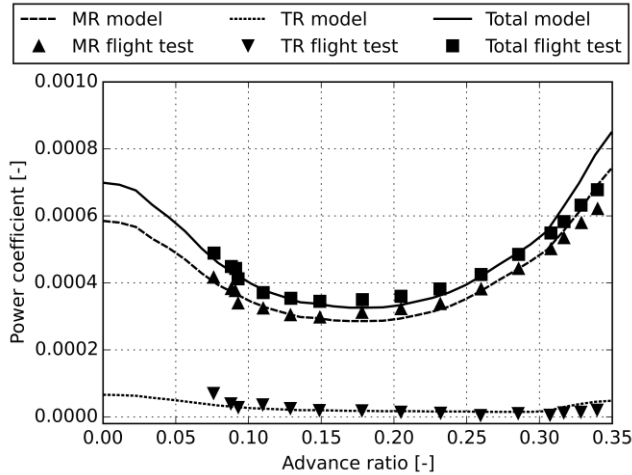


Figure 4 Rotorcraft model flight dynamics trim results

Engine Modeling

A model of the General Electric T700-GE-700 engine which powers the UH-60A Black Hawk helicopter was developed in TURBOMATCH. This powerplant is a small turboshaft engine in the 1100-1350 kW class, equipped with a five-stage axial and a single-stage centrifugal compressor; a conventional annular combustion chamber; a two-stage axial gas generator turbine; and a two-stage uncooled power turbine [21, 22]. A scheme of this engine is shown in Fig. 5.

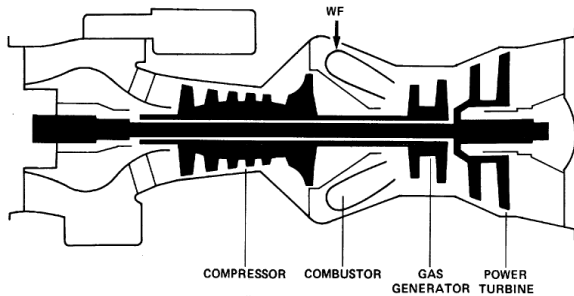


Figure 5 General Electric T700-GE-700 turboshaft engine layout [21]

The DP used to develop the engine model corresponds to the Maximum Continuous Power (MCP) rating at SL-ISA conditions (Table 2). The turbine cooling and engine bleeding mass flows are defined relative to the inlet mass flow rate, and the values are based on mass-flow functions specific of the T700-GE-700 engine employed by Ballin [21].

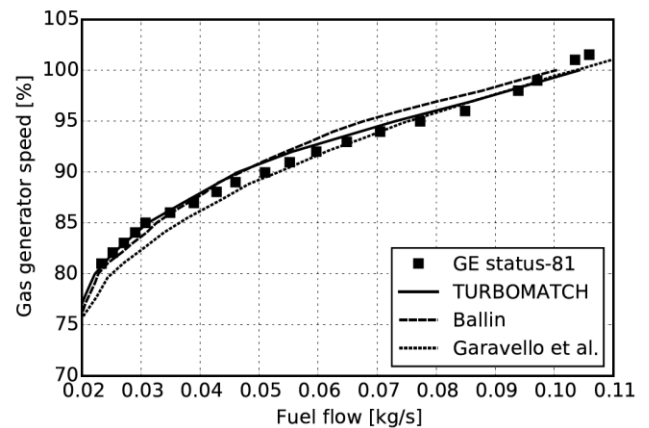
Table 2 Engine model design point at MCP SL-ISA conditions

Inlet pressure recovery [-]	0.986
Design mass flow [kg/s]	4.170
Compressor section	
Axial compressor PR [-]	5.3
Centrifugal compressor PR [-]	2.8
Axial compressor η [-]	0.821
Centrifugal compressor η [-]	0.821
Cooling flow bleed percentage [%]	8.46
Engine bleed percentage [%]	1.06
Combustion section	
Combustion efficiency [-]	0.984
Combustor pressure drop [%]	4.0
TET [K]	1440
Fuel flow [kg/s]	0.0807
Turbine section	
Gas generator turbine η [-]	0.852
Free power turbine η [-]	0.845
Shaft power [kW]	987.0

Engine Model Validation

In order to ensure the engine model created is accurate enough to simulate the performance of the T700-GE-700 engine, some steady-state performance maps collected in [21] were used for the model validation. These maps were created by a simulation software called GE status-81 developed by the engine manufacturer. This code is a comprehensive analysis-oriented model which is used for detailed representation of the engine thermodynamic cycle [21]. The maps considered herein for the engine model validation provide the gas generator speed and shaft power as a function of the fuel flow at SL-ISA conditions (Fig. 6).

a)



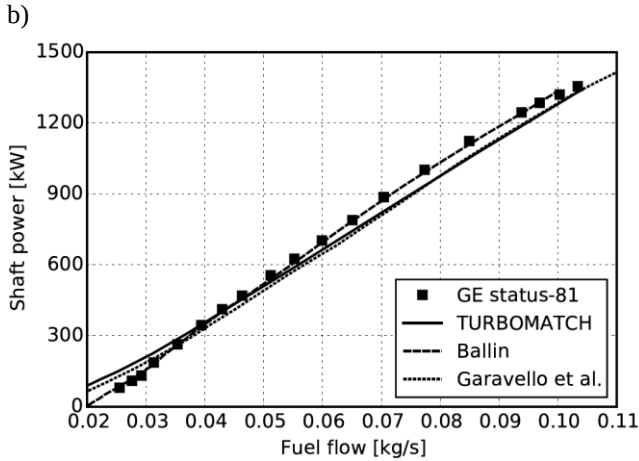


Figure 6 TURBOMATCH engine model validation: (a) Gas generator speed vs. Fuel flow, (b) Shaft power vs. Fuel flow

The agreement between the model and the software in terms of both gas generator speed and shaft power is good for the complete range of fuel flow rates provided by the manufacturer. This is especially critical for the analysis of helicopter performance, where high and low power conditions are expected at different phases of the mission. The results obtained from two previous simulations performed by Ballin [21] and Garavello *et al* [23] are also provided for comparison, and are very similar to the results obtained in this work.

Emissions Modeling

In order to estimate the NO_x emissions produced during the helicopter operation, an engine combustor model was created in HEPHAESTUS after the T700-GE-700 combustion chamber architecture and operating conditions. The GE T700/CT7 engine family uses a straight-through annular combustion system of 12.5 cm in length utilizing a machined ring film cooled construction and 12 low-pressure air blast fuel injectors [22]. The combustor geometry shown in Fig. 7 is implemented in HEPHAESTUS through the definition of the volume and air mass flow distribution in four combustor regions: flame front (FF), primary zone (PZ), intermediate zone (IZ) and dilution zone (DZ).

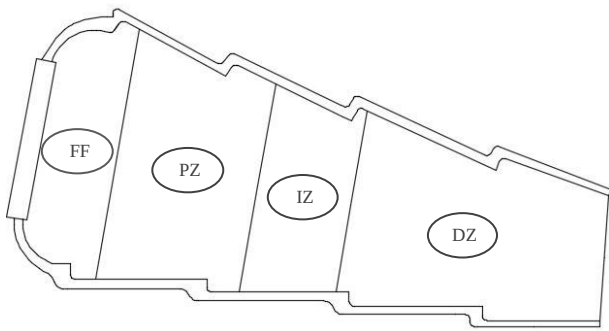


Figure 7 GE T700-GE-700 engine combustor layout

The combustor dimensions implemented in the model were obtained from combustion system cross section plots provided by Monty *et al* [24], whilst the air flow distribution along the combustor is based on a combustor engine model proposed by Fakhre *et al* [25] for a General Electric T700 family engine.

Emissions Model Validation

The ability to predict the pollutant emissions of CO_2 and NO_x at different operating conditions must be verified in order to assess the adequacy of the emissions model. CO_2 production is coupled with fuel consumption through the combustion reaction stoichiometry. Since fuel consumption is well predicted by the model (Fig. 6), the CO_2 emissions will be properly predicted as well. However, NO_x production is affected by operating factors such as gas temperature and pressure, fuel type, equivalence ratio and residence time within the combustor [26]. Thus, the capability of the model to predict the NO_x formation has to be validated. To that end, the operating conditions of the experiments conducted by Cohen at the NASA Lewis Research Center for the General Electric T700/CT7 engine family combustor [22] were simulated in the HEPHAESTUS model. The experiments were performed for JP-4 and JP-5 fuels. The experimental results for the JP-5 are used for validation (Fig. 8) since this fuel has a hydrogen content similar to the Jet A fuel, which is the aviation working fuel in HEPHAESTUS.

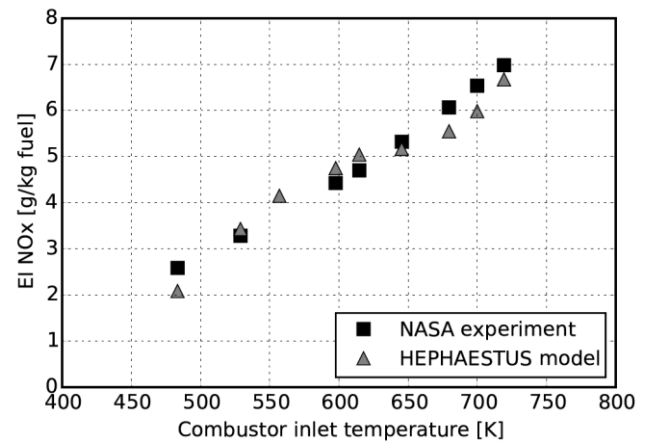


Figure 8 HEPHAESTUS emission model results comparison: EI NO_x vs. Combustor inlet temperature

The model is able to predict the trend of the NO_x emissions with variations in combustor inlet temperature (Fig. 8), NO_x emissions are slightly under predicted at lower power settings (lower inlet combustor temperature), whilst the opposite occurs at higher power conditions. Overall, a good agreement with the experimental results is observed and the NO_x production trend is accurately predicted by the simulation model. An error of 19% is observed at the lowest values of combustor inlet temperatures, whilst at the opposite extreme of

the curve the incurred error is around 14%. For the rest of points, the error in the NO_x prediction lies below 5%.

ROTORCRAFT-ENGINE PERFORMANCE

The effect of the environmental parameters considered in the present study i.e. ambient temperature and flight altitude, and the compressor degradation on the rotorcraft-engine performance are presented in this section.

Firstly, the effect of altitude and temperature on the UH-60A Black Hawk shaft power demand is analyzed (Fig. 9). Then, the variation of the NO_x production rate with helicopter air speed including the effects of ambient temperature and flight altitude is presented in Fig. 10. For the sake of conciseness, the fuel flow variation with air speed is not shown herein since its variation with engine shaft power is almost linear, and the fluctuations in fuel flow are proportional to changes in the environmental parameters (Fig. 11).

The shape of the power curves shown in Fig. 9 corresponds to the classic ‘bucket-shape’ curve characteristic of helicopters and highly influenced by the main rotor power requirement. At lower speeds, the power demand is driven by the induced term, whilst at higher speeds the parasitic drag of the fuselage is the dominant component. The fact that the induced power is inversely proportional to air density, and the parasitic term is proportional to it [1], explains the variations of the power curve shape with flight altitude and ambient temperature observed.

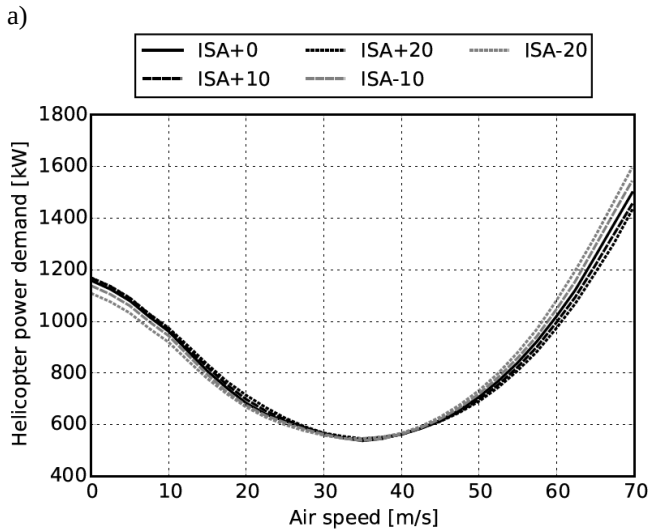
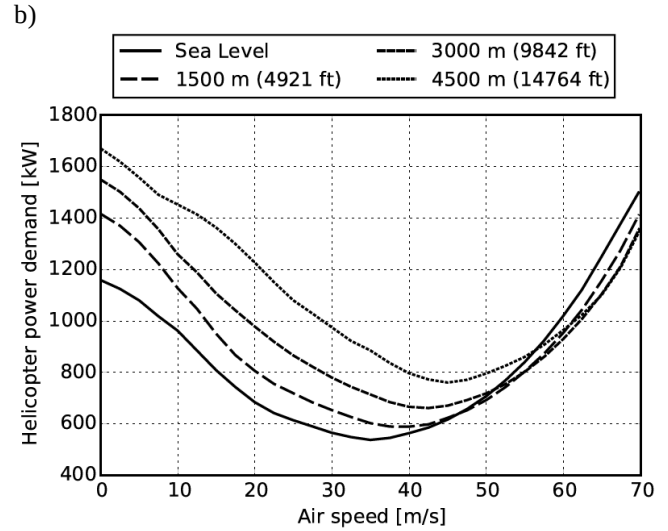
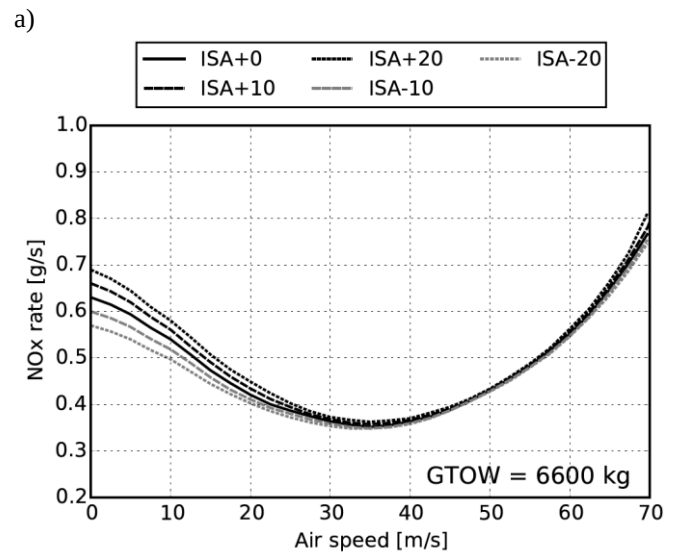


Figure 9 Helicopter power demand in forward flight: (a) at different temperatures, (b) at different altitudes

As observed in Fig. 12, NO_x emissions are proportional to engine shaft power which explains the trend observed in Fig. 10 and the fact that the speed of minimum NO_x production coincides with the speed of minimum power. However, the effect of temperature (Fig. 10a) is not exactly the same. The effect of temperature is not dominant at low power settings, so the reduction of power with temperature comes with a reduction in the NO_x emissions in this region. As power increases, although the power requirement decreases with the rise of temperature, its effect is not enough to offset the increase in NO_x formation with temperature (Fig. 12a), and so the latter effect prevails. As a result, it is observed that the NO_x rate increases with ambient temperature regardless of the flight speed.



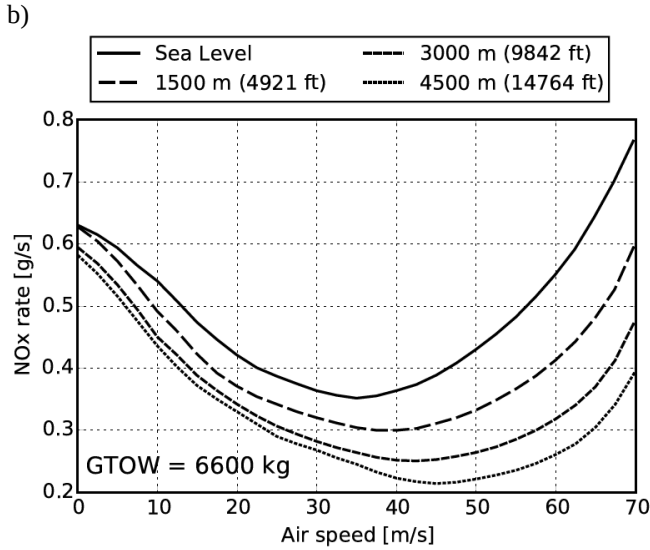


Figure 10 Helicopter NO_x formation rate in forward flight: (a) at different temperatures, (b) at different altitudes

Considering the effect of flight altitude in the NO_x emissions rate (Fig. 10b), it is observed that the lower the altitude the lower the pollutant emissions at any airspeed. Regardless, the increased power requirement at low power settings due to the rise in altitude, the descent in air mass flow and combustor inlet pressure (Fig. 14) dominates and so, the NO_x rate reduces. At higher flight speed, the drop in power requirement enhances the NO_x formation reduction which leads to a decrement around 50% for a flight speed of 60 m/s at a flight altitude of 4500 m.

The effect of altitude, temperature and compressors degradation on the GE T700-GE-700 engine performance is shown in Figs. 11 and 12. The compressor deterioration was simulated with a compressor efficiency and flow capacity degradation of 2.5% and 5%, respectively. It was also assumed that both axial and radial compressors were equally degraded.

Engine fuel flow is slightly affected by the ambient temperature due to the changes in the work required by the compressor with inlet air temperature. The fuel flow at hotter conditions is larger than the fuel flow at colder conditions since the compression work is higher and vice versa (Fig. 11.a).

However, the effect of altitude on fuel flow is more relevant (Fig. 11.b). As a result of the pressure drop of the engine inlet air with altitude, the engine works with an increased pressure ratio with translates in a gain in cycle efficiency and so, a reduction in the fuel consumption. Compressor degradation, as expected, has a negative effect on the engine efficiency. The reduction in flow capacity of the degraded component requires an increase in specific power in order to deliver the same shaft power. This increase in specific power is achieved by burning extra fuel in order to rise the TET. Together with this effect, the reduction of the compressor

efficiency impairs the cycle efficiency, which further contributes to the total fuel flow increase.

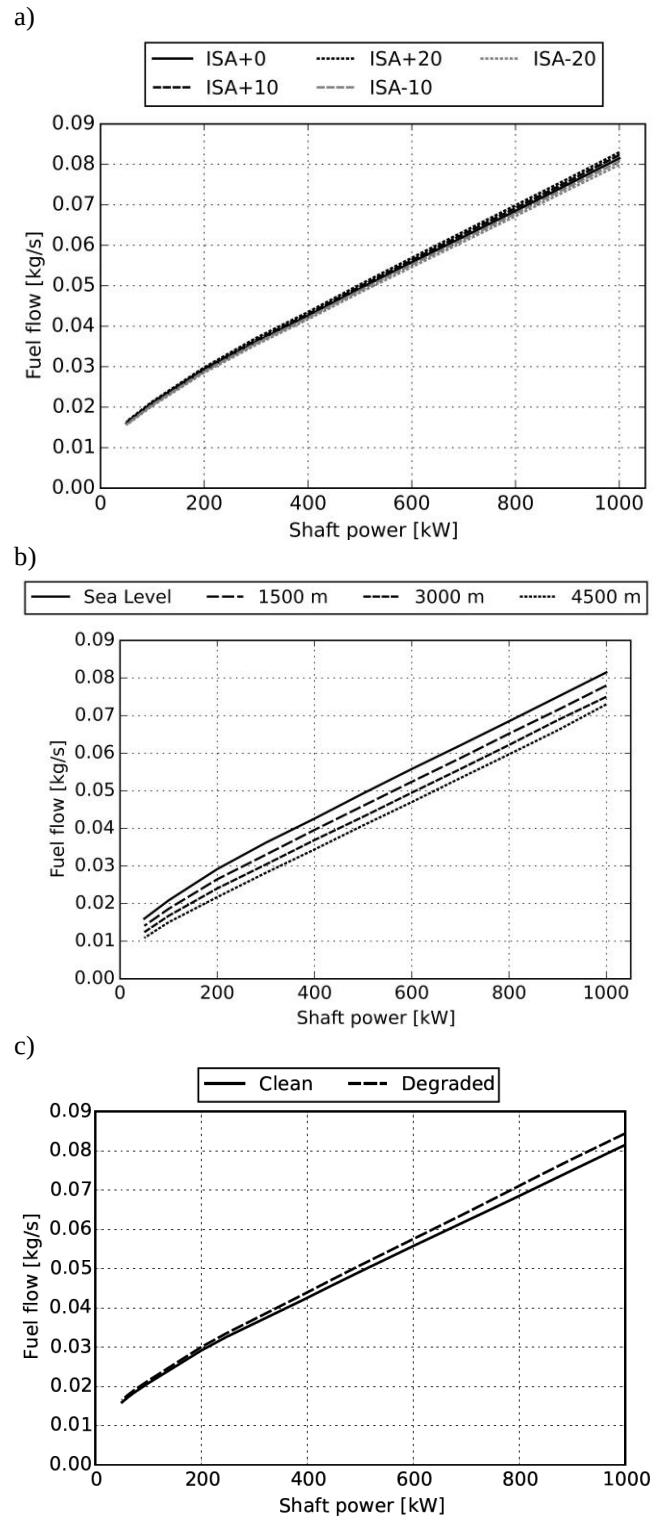


Figure 11 Fuel flow vs. Shaft power: (a) effect of ambient temperature, (b) effect of flight altitude, (c) effect of compressor degradation

NO_x emissions, as they are computed in the present analysis, depend on the air conditions at the inlet of the combustor, the airflow supply going into the burner and the amount of fuel employed in the combustion. Therefore, to explain the behavior of NO_x with ambient temperature, the combustor inlet temperature trend is plotted (Fig.13). The increase in this parameter with the ambient temperature, together with the slightly increase in fuel flow (Fig. 11.a) explains the trend observed in (Fig. 12.a).

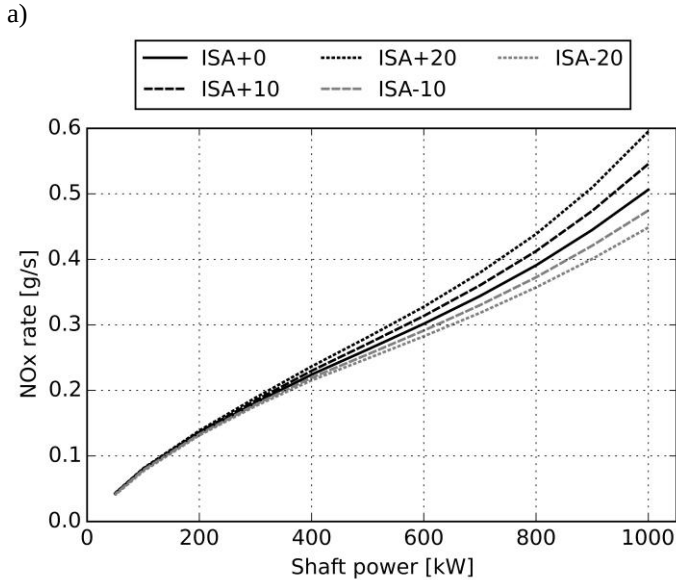
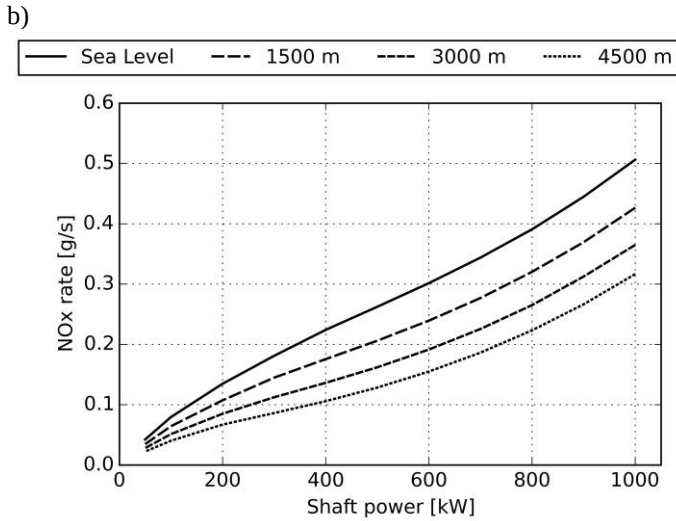
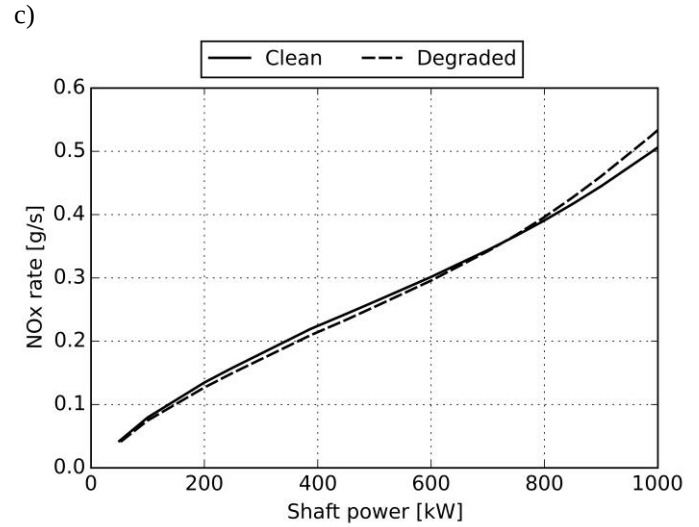


Figure 12 NO_x rate vs. Shaft power: (a) effect of ambient temperature, (b) effect of flight altitude, (c) effect of compressor degradation

The influence of altitude in the NO_x emissions is shown in Fig. 12.b. The combined effect of pressure and air flow drop at the inlet of the combustor (Fig. 14) added to the effect of fuel reduction with flight altitude (Fig. 11.b) explains the reduction of NO_x production with flight altitude. It is emphasized that the effect of altitude on the NO_x rate is more sizeable than the effect of ambient temperature. The effect of compressor degradation on NO_x emissions is small compared to flight altitude or ambient temperature. The change in combustor inlet conditions i.e. air pressure and temperature, are almost negligible and only fuel flow (Fig. 11.c) and airflow are slightly affected. For the degraded engine it is observed that NO_x emissions are slightly lower at low power settings and become higher towards the end of the power curve. This behavior can be explained by the distribution of flame temperature and equivalent ratio of the combustor Flame Front and Primary Zone (Fig. 15). These are the two parts of the combustor responsible for the NO_x production since the flame temperatures observed in these regions are high enough to trigger the NO_x formation mechanisms. It is observed that the equivalent ratio in the FF region is above the stoichiometric value, and so, the increase in fuel flow of the degraded engine contributes to slightly lower the flame temperature. On the other hand, the equivalent ratio on the PZ is below the stoichiometric value, which implies, that the increase in fuel contributes to rise the flame temperature on this region. The flame temperature of the PZ is much lower at low power settings than the temperature at the FF, and so is its contribution to the NO_x formation. That explains that the trend in Fig. 10.c. at low shaft power is dominated by the slight reduction in flame temperature at the FF. However, the temperature at the PZ rises continuously (Fig. 15), which causes a change in trend in the NO_x rate at a shaft power around 700 kW. At this point, the production of this pollutant in the PZ becomes significant and its relevance in the total NO_x account

increases. As the flame temperature in the PZ in the degraded engine is higher (Fig. 15), the NO_x production rate is also higher, and as a result, at the end of the power spectrum an increase of NO_x formation is observed for the degraded engine.

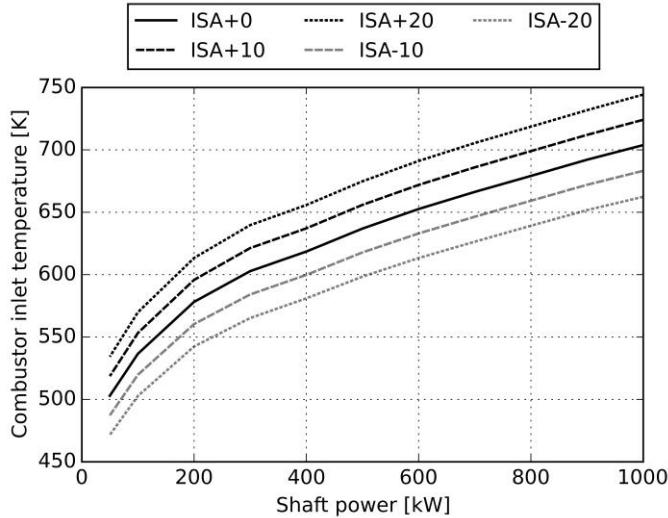


Figure 13 Combustor inlet temperature vs. Shaft power at different ambient temperatures

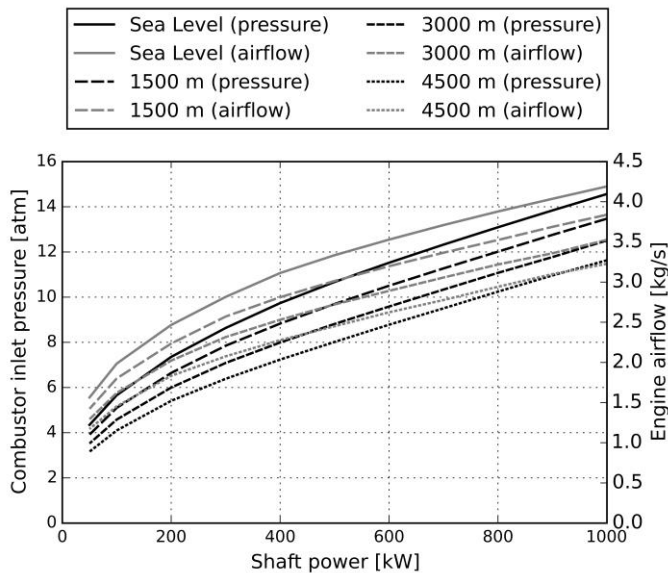


Figure 14 Combustor inlet pressure and airflow vs. Shaft power at different altitudes

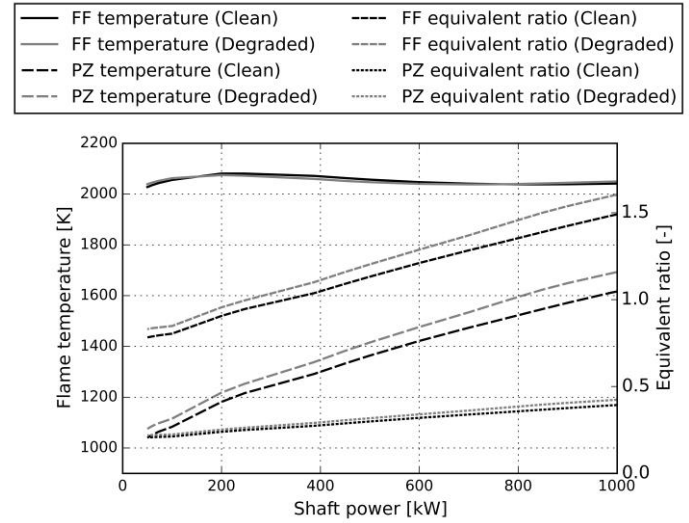


Figure 15 Combustor FF and PZ flame temperature and equivalent ratio vs. Shaft power: effect of degradation

CASE STUDY

The helicopter model described in previous sections is used to assess the overall impact of the environmental conditions on the performance of the helicopter at mission level. Particularly, the effect of high temperature, dust ingestion, and high altitude on fuel consumption and NO_x production is evaluated. Two missions are envisioned for this purpose. Firstly, a theoretical EMS mission over a hot desert area is designed to assess the effect of high temperature and dust ingestion. Secondly, a SAR mission over an elevated cold area ('High & Cold' scenario) is considered so as to evaluate the effect of low temperature and low air density on helicopter operation.

Emergency Medical Service (EMS) Mission

The scenario chosen for the hypothetical EMS mission is situated in the Mojave Desert area. In particular, the helicopter is considered to take-off from the Palm Springs International Airport, California, to pick-up several civilians in distress from an accident location in the Joshua Tree National Park, and transport them to the Robert E. Bush Naval Hospital in Twentynine Palms, California. The geographical trajectory of the mission in global coordinates is reproduced in Fig. 16.a. The mission altitude and airspeed profiles are shown in Fig. 16.b. It is observed that the mission comprises three legs. The flight altitude of each corresponds to an AGL average altitude of 450 m, bearing in mind the ground altitude fluctuations over the flight path. The cruise speed for the three legs is 60 m/s. Climb and descent rates are held fixed at 5m/s, and the idle segments are assumed to be operated at 20% of DP (Maximum Continuous Power) engine shaft power. A hover segment of 60 seconds duration is completed before any climb maneuver. The mission payload breakdown is detailed in Table 3.

a)

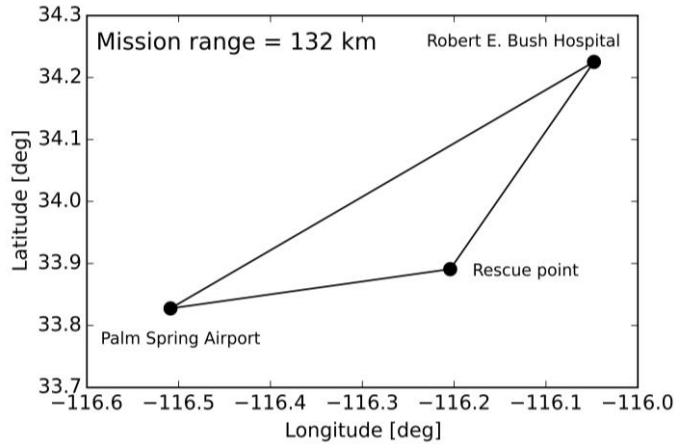
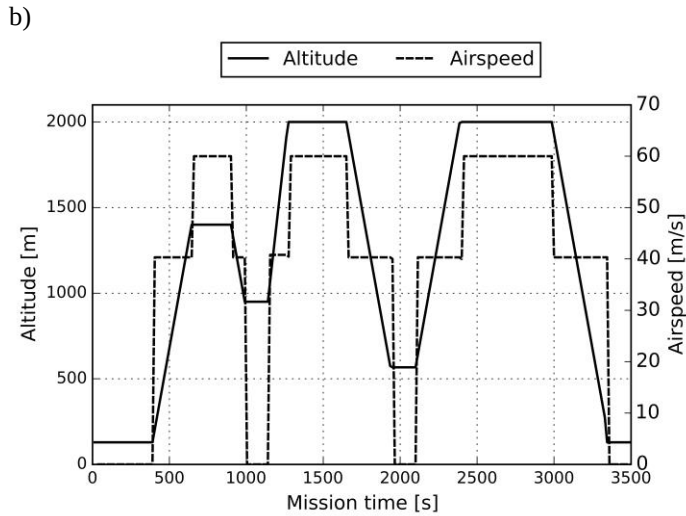


Figure 16 EMS mission definition: (a) geographical trajectory, (b) altitude and airspeed variation with mission time

Table 3 EMS mission payload breakdown

Payload type	Quantity	Weight [kg]
Stretcher	6	300
Medical attendant	1	90
Medical assistant	1	90
Patient	3	270
Medical equipment	-	300
Total weight		1050

The arid nature of the Joshua Tree National Park and its surroundings together with the high temperatures justify the selection of this location to simulate the hot sandy desert conditions. Particularly, the temperature and engine degradation conditions summarized in Table 4 are simulated. The mission was first simulated at ISA and clean engine conditions. Then, the temperature was modified to assess the effect of hot temperature in helicopter performance. The value of ISA +24 (103°F) corresponds to the average high temperature in July (most torrid month) measured in Twentynine Palms according to US Climate Data [27]. Finally, the sand and dust ingestion

effects are added as engine compressor performance deterioration. A certain amount of these particles manages to get through the filtration system and deposits on compressor blades reducing efficiency, η , and mass flow capacity, Γ . This deterioration cause is known as fouling and is more commonly observed in compressor rather than turbine components. Therefore, two different pair of compressor degradation levels were considered in the analysis based on engineering judgment and typical values detected in real engines [28]. It was assumed that both axial and radial compressors were equally degraded.

Table 4 EMS mission simulation cases

Case	ISA deviation	Compressor degradation	
		η (%)	Γ (%)
1	0	0	0
2	+24	0	0
3	+24	1.25	2.5
4	+24	2.5	5

Search and Rescue (SAR) Mission

For the SAR mission the helicopter was considered to complete a research pattern in the Rocky Mountains region. To that end, the helicopter takes-off from the Rose Medical Center Heliport in Denver, Colorado. From this location the helicopter transits to the Mt. Evans where it performs a circular search pattern of 5 km radius. After this first loop the helicopter moves towards a mountain resort nearby where it repeats the same searching maneuver until the civilians in distress are found and collected. The helicopter transits then back to the hospital of origin where the rescued civilians receipt medical attention (Figs. 17.a and 17.b). In this case, the mission includes three cruise legs and two loiter segments. As in the EMS mission, the cruise segments are operated at around 450 m AGL and 60 m/s, and same assumptions were kept for the climb, descent and idle segments. The loiter leg is flown at a reduced altitude of 60 m and at 30 m/s, and the helicopter hovers for 10 minutes during the rescue operation. The mission payload breakdown is detailed in Table 5.

Table 5 SAR mission payload breakdown

Payload type	Quantity	Weight [kg]
Medical attendant	1	90
Medical assistant	1	90
Civilians	8	720
Rescue equipment	-	50
Total weight		950

a)

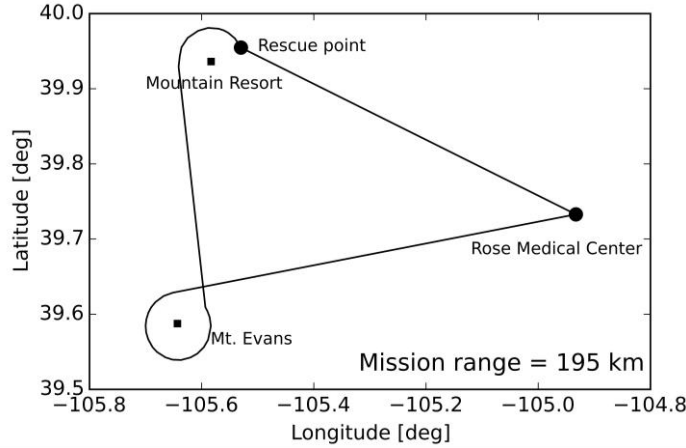
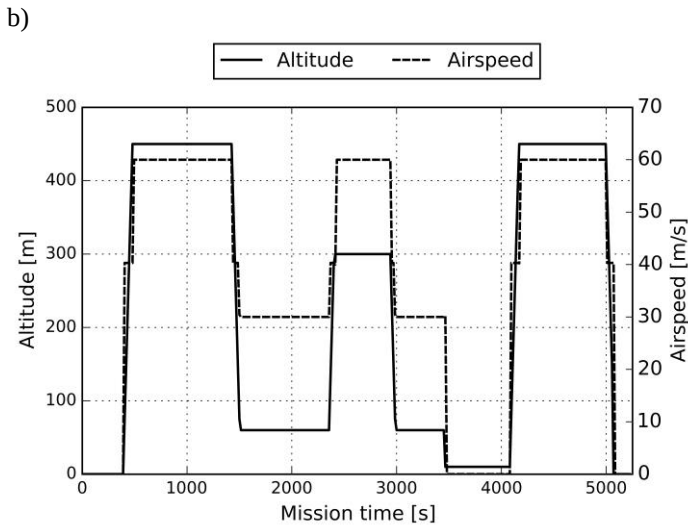
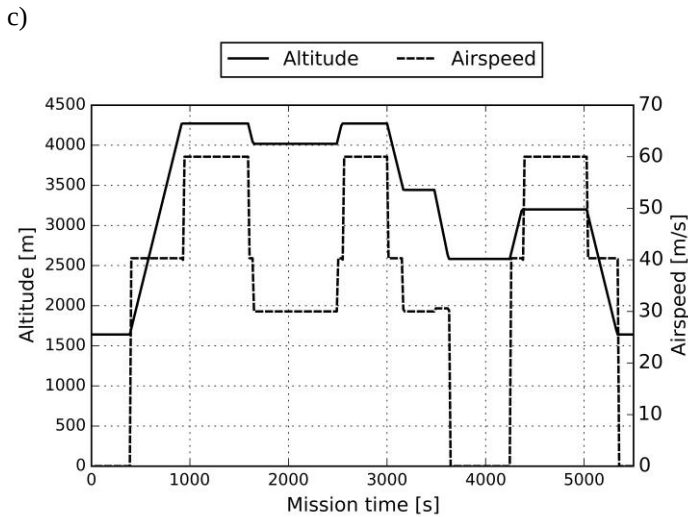


Figure 17 SAR mission definition: (a) geographical trajectory, (b) altitude and airspeed variation with time (SL scenario), (c) altitude and airspeed variation with time ('High & Cold' scenario)

The elevation of the region and its climate are ideal to analyze the effect of high altitude and low temperature conditions on helicopter performance. The average elevation of the area covered by the helicopter trajectory is around 2800 m (9185ft) whilst the temperature considered is ISA -23 (18°F). This value of temperature corresponds to the average low temperature in January (coolest month) registered in Denver by US Climate Data [29]. To quantify the effects of the environmental conditions on helicopter fuel consumption and emissions, the results obtained under these particular conditions of altitude and temperature are benchmarked against the results produced by the simulation of the same helicopter trajectory at standard temperature and SL conditions. The altitude and airspeed profile of this mission are reproduced in Fig. 17.c. Same operational procedures were applied for the benchmarking mission. As a consequence of the increased flight altitude, the helicopter spends more time in climb and descent under the 'High & Cold' scenario. Therefore the mission times are slightly different from each scenario, namely, 5220 seconds (87 min) for the SL scenario and 5490 seconds (91.5 min) for the 'High & Cold' scenario.

RESULTS AND DISCUSSION

The results obtained for the EMS missions are first presented in Table 6 and Figs. 18 and 19. Note that the results of shaft power, fuel flow and NO_x emissions in Figs. 18 and 19 are values per engine. As a consequence of the high temperature (Case 2), the mission fuel and NO_x emissions increase compared to the reference mission outputs (case 1). The addition of compressor degradation (Cases 3 and 4) further increases the mission fuel, whilst it slightly reduces overall NO_x emissions.

Table 6 EMS mission fuel burn and NO_x emissions results

Case	Fuel [kg]	NO_x [kg]	% Δ Fuel	% Δ NO_x
1	269.3	1.210	-	-
2	274.7	1.298	2.02	7.32
3	279.2	1.291	3.68	6.73
4	283.7	1.290	5.37	6.63

In agreement with the trend observed in Fig. 9.a, the rise in ambient temperature reduces the power required by the main rotor at cruise ($V=60$ m/s), whilst the power demand at hover is increased (Fig. 18.a). In the descent and climb segments, where the effect of the thinner atmosphere prevails over the reduction in airframe drag, the rise in ambient temperature also translates in a slightly higher power demand. This fluctuation in the main rotor power directly affects the fuel consumption as engine fuel flow is proportional to the shaft power (Fig. 11). Apart from the effect on main rotor performance, the higher ambient temperature also impairs the efficiency of the engine (Fig. 11.a),

which shifts the fuel flow trend up (Fig. 18.b) and balances out the effect of reduced main rotor power at cruise conditions. Therefore, the overall effect of the ambient temperature rise is an increased in the mission block fuel as seen in Table 6. However, the magnitude of this effect is mission dependent, as missions with longer cruise segments will be less penalized in fuel consumption than those with a high number of climb & descent cycles.

NO_x emissions, like fuel flow, are proportional to shaft power (Fig. 12), and so a similar trend is observed for the NO_x production over the mission (Fig. 18.c). Equally to the fuel flow distribution, the rise in ambient temperature has also a negative effect on the NO_x production rate (Fig. 11.a), and so, the overall emissions are penalized as shown in Table 6.

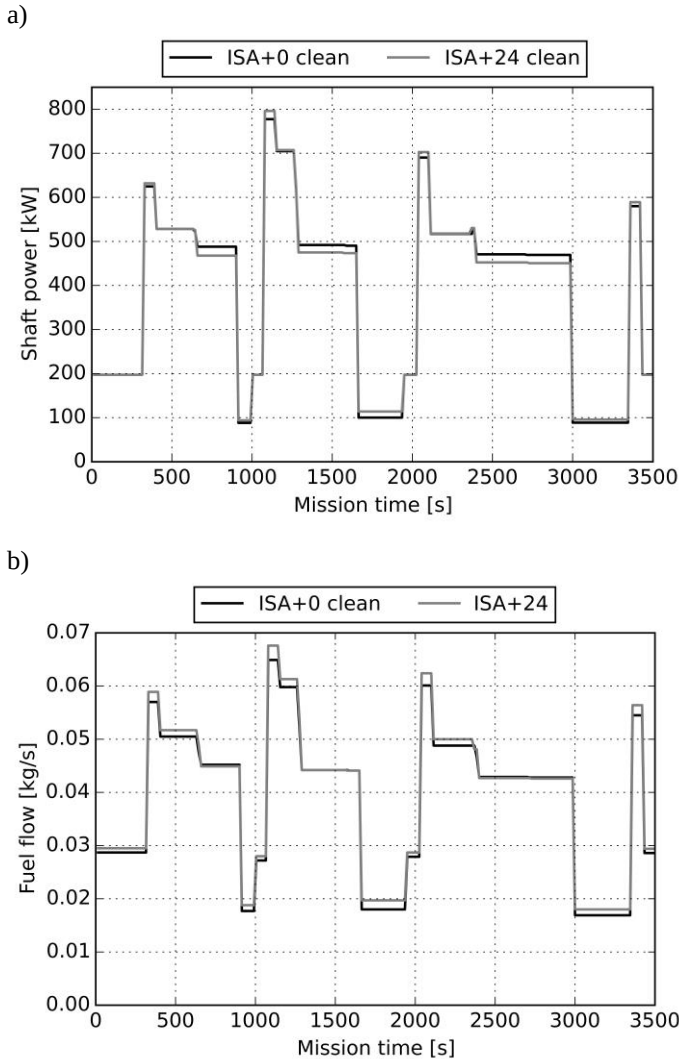
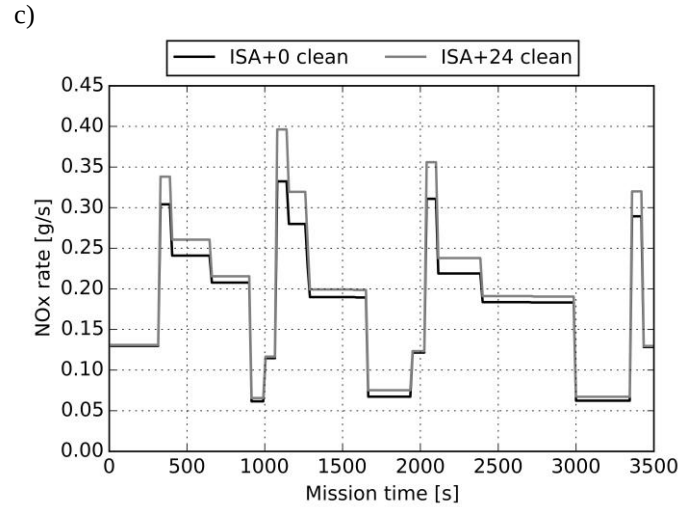


Figure 18 Effect of temperature on EMS mission: (a) shaft power comparison, (b) fuel flow comparison, (c) NO_x rate comparison

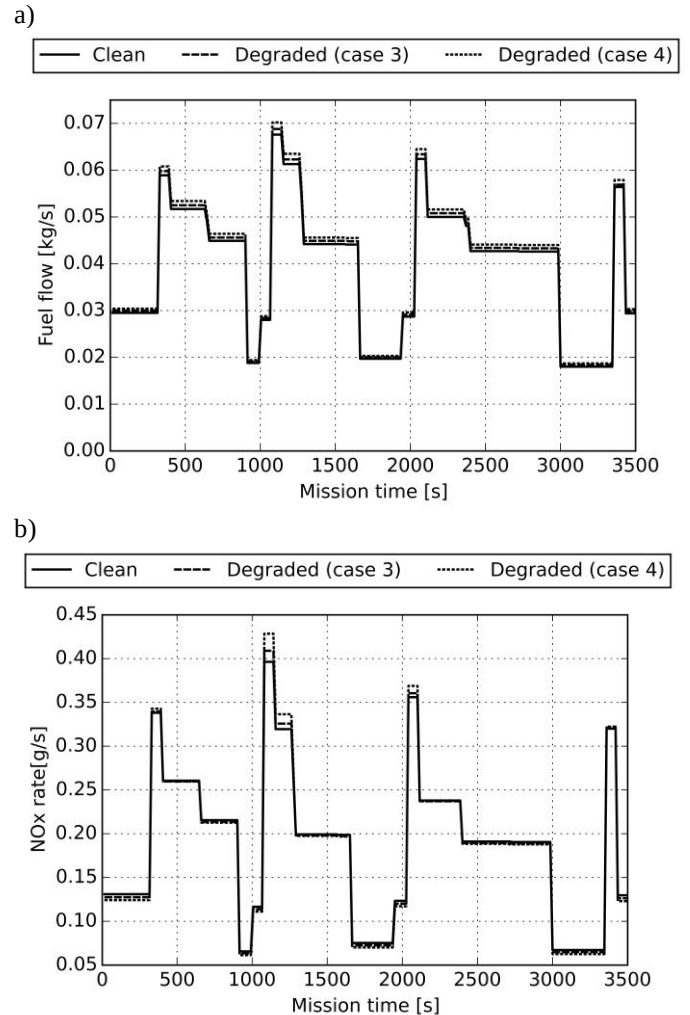


Figure 19 Effect of degradation on EMS mission: (a) fuel flow comparison, (b) NO_x rate comparison

When compressor degradation is considered, the fuel flow at each flight segment increases (Fig. 19.a). This result is directly linked with the fuel flow distribution observed in Fig. 11.c and explains the increase in mission fuel for Cases 3 and 4 observed in Table 6. Regarding the NO_x production over the mission (Fig. 19.b), it is observed that compressor degradation only increase the emissions with respect to the clean configuration in those segments with a high power demand, i.e. the four hover segments and the second climb segment (after collection of the civilians in distress). On the other hand, in those segments with a low power consumption, such as descent and idle, the NO_x production rate of the degraded configuration is lower. This distribution of the NO_x emissions over the mission is in agreement with the trend previously obtained for the effect of compressor degradation on NO_x formation (Fig. 12.c). For the particular mission simulated, the helicopter spends more time in descent and idle conditions than at hover; therefore the NO_x production is reduced compared with the clean engine configuration. However, this cannot be regarded as a general result, since the same flight path operated with an increased payload or an alternative flight path with a different proportion of hover segments and idle/descent segments may generate a different NO_x emissions response.

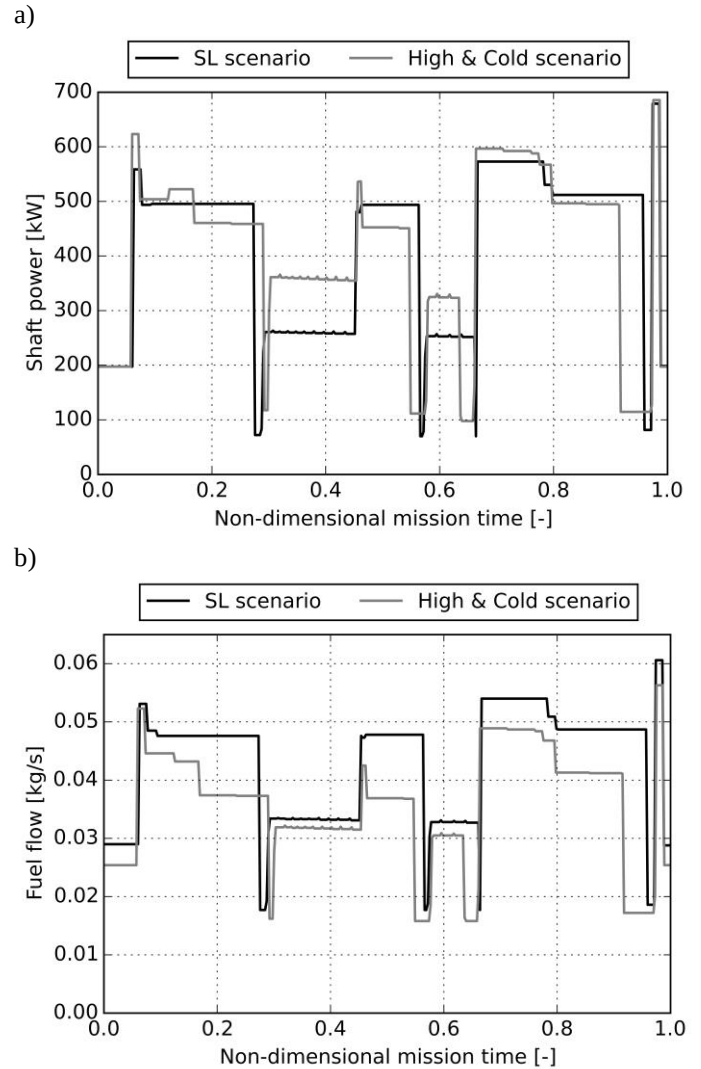
The results obtained for the SAR mission at the two different scenarios simulated are presented in Table 7 and Fig. 20. As before, the results in Fig. 20 are values per engine.

Table 7 SAR mission fuel burn and NO_x emissions results

Case	Fuel [kg]	NO_x [kg]	% Δ Fuel	% Δ NO_x
ISA/SL	443.9	2.249	-	-
High & Cold	391.1	1.358	-11.89	-39.60

In the ‘High & Cold’ scenario simulated, the high altitude and low temperature have opposed effects on the power consumed by the main rotor. In fact, lower temperature implies a denser atmosphere, whilst the opposite is achieved with the increase in flight altitude. From the two effects, the contribution of flight altitude to helicopter power demand is dominant (Fig. 9). Therefore, for the ‘High & Cold’ mission the power consumed by the rotor in those segments driven by the induced power (hover, climb and descent) is higher, whilst at cruise, where the parasitic drag is the dominant effect, the power demanded by the rotor is lower (Fig. 20.a). In contrast to the operation at cruise, the power required to fly the loiter segments is higher for the ‘High & Cold’ scenario, due to the reduced helicopter airspeed (Figs. 17.b and 17.c). In fact, at the loiter speed ($V=30\text{m/s}$), the power consumed by the main rotor is still governed by the induced term (Fig. 9). Note that a non-dimensional time has been used to plot Fig. 20 since the two scenarios have slightly different mission times.

Regarding the operation of the engine, the high altitude and low temperature of the ‘High & Cold’ scenario have a positive effect in the engine fuel consumption (Figs. 11.a and 11.b). This increase in engine efficiency translates in a fuel flow reduction in all the mission segments. For the particular combination of temperature and altitude of the mission simulated, it is observed that the engine efficiency offsets the power increase in those segments previously mentioned, whilst at cruise the combined effect of reduced main rotor power and improved engine efficiency translates in a sizeable 20% fuel reduction over the cruise segment (Fig. 20.b). This fuel consumption distribution over the mission explains the results shown in Table 7. Similar comments apply for the NO_x production along the mission (Fig. 20.c). The low temperature and high altitude combination impairs the formation of NO_x in the combustor (Fig. 12.a and 12.b), resulting in the overall emission reduction observed in Table 7.



c)

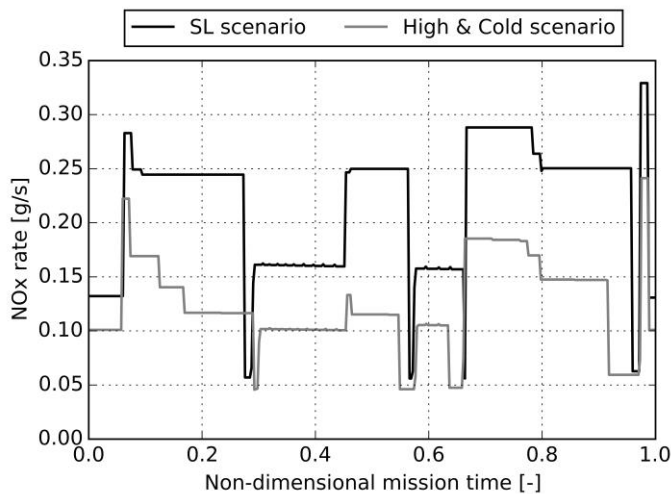


Figure 20 Effect of altitude and temperature on SAR mission: (a) shaft power comparison, (b) fuel flow comparison, (c) NO_x rate comparison

CONCLUSIONS

This paper described the effects of environmental conditions on helicopter performance in terms of fuel consumption and NO_x emissions. In particular, the impact of temperature, altitude and dusty air were considered. A multidisciplinary helicopter flight performance simulation framework developed and validated at Cranfield University has been used to simulate the different aspects of the helicopter operation. A model of a representative TEM helicopter after the UH-60A Black Hawk helicopter has been developed and implemented in the simulation software. The different components of the helicopter model have been described and validated against experimental and manufacturer data.

A case study based on an EMS mission over a hot desert location and a SAR mission in a mountain region was developed as a representative scenario of the TEM helicopter operation. High ambient temperature and compressor degradation, and flow capacity and efficiency drop, were reproduced in the EMS mission, whilst high altitude and low temperature conditions ('High & Cold' scenario) were simulated in the SAR mission.

For the EMS mission simulated it was highlighted the negative effect of high temperature in fuel consumption and NO_x emissions, despite of the reduction in main rotor power observed at cruise conditions. As a result, an increase in mission fuel of 2% was obtained for the hotter mission. Compressor degradation further increases the mission fuel in an additional 3% (for the most severe degradation case), although its effect on NO_x formation may be regarded as negligible. At the particular conditions simulated herein, a slightly reduction in mission NO_x was obtained, but the positive or negative contribution of compressor degradation to the NO_x account was

shown to be dependent on the level of shaft power required by the main rotor.

Regarding the SAR mission, it has been highlighted that the effect of altitude on the main rotor power is dominant over the effect of temperature. Therefore, under realistic ambient temperature fluctuations, the power consumed by the rotor will be driven by flight altitude (ambient pressure), in such a way that the power consumed in segments driven by the parasitic drag will drop with altitude, and the opposite will occur for segments driven by the induced term. It has been also shown that the high altitude and low temperature combination has positive effects in fuel consumption and NO_x production offsetting the increased power in hover, climb, descent and loiter in the particular mission, and leading to a reduction of 12% and 40% in mission fuel and NO_x, respectively.

The case study presented herein is an example of the simulation capabilities of the methodology developed. The impact of different environmental conditions and different engine component degradation levels on the helicopter at any user defined flight trajectory can be simulated by the performance simulation framework described in this study. The present work provides a meaningful insight of the extent the design performance of a given helicopter is affected by the environmental conditions of the operational scenario.

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Assessment of the effect of environmental conditions on rotorcraft pollutant emissions at mission level

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2017-08-17

American Society of Mechanical Engineers (ASME)

<https://doi.org/10.1115/GT2017-63440>

Ortiz-Carretero J, Castillo Pardo A, Pachidis V, Goulos I. (2017) Assessment of the effect of environmental conditions on rotorcraft pollutant emissions at mission level. In: ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition (GT2017), 26-30 June 2017, Charlotte, NC, USA