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Aero engine compressor cooling by water injection - Part 1: Evaporative compressor model

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ABSTRACT

The need for more fuel-efficient turbofan engines has led to a rise in compressor pressure ratio and turbine inlet temperature respectively. The latter has been possible with advancements in turbine blade technology. Nevertheless, this higher temperature during combustion increases the production of thermal Nitrogen Oxides. Contrary to this high-pressure, high-temperature aero-engine design trend, regulations are pushing towards capping or reducing emissions. Injecting atomised water into a jet engine is an alternative to mitigate Nitrogen Oxides that is applied extensively to stationary gas turbines. The application for jet engines is very limited and dates back to the early Boeing 707 and 747 for thrust augmentation. The focus of this study is to investigate the performance benefits of water injection when applied to 2 and 3-spool compressors, under a wide range of different environmental conditions, and for different injection properties. In this first paper, a thermo-analytical compressor model with water droplet investigations in the Lagrangian frame of reference is explored. The methodology is applied to two different engine architectures, representative of modern turbofan engines. This water injection study focuses on cooling the core and shows that the percent reduction in compressor discharge temperature is promising over a wider range of ambient conditions than expected. The effect of droplet sizes or quantity utilised were seen to be more influential. The 3-spool compressor also appears to benefit more from water injection, mainly due to the higher operating pressures and temperatures found on the Intermediate Pressure Compressor which enables more efficient evaporation, as compared to a booster compressor. Given the design of this compressor, two locations of injections were considered. Reductions in Compressor Discharge Temperature of 60 and 80 K were seen for the 2 and 3-spool engines, for a 2% injection ratio, accompanied by reductions in specific compressor work of 16 and 17%. Part 2 of this study has considered boundary conditions obtained here, to investigate the performance and emissions of complete jet engines.

1. Introduction

The rise in air travel demand estimated at 5% per year [1] has brought optimism about the future of the civil aviation industry. This, of course, has been met with more public discourse and regulations related to increasing environmental impact. Block and Igie [2] shows different measures focused on mitigating the environmental impact of aviation at and around airports. The study points out that most of the proposed solutions are focused on reducing CO, HC and CO_2. Only a few measures address Nitrogen Oxides (NO_x) emissions. Daggett et al. [3] estimate a 47% reduction in NO_x when 2% water to air ratio is injected into the core flow of the engine. The mechanism for this reduction is the cooling of the thermodynamic cycle, which also reduces the specific compressor work, enabling higher useful work outputs. With this improvement in pressure ratio, less fuel can be utilised for the same thrust requirement, which brings about an improvement in the Specific Fuel Consumption (SFC). The use of such a system on an aircraft, at take-off and climb when the engine is operated at peak Turbine Inlet Temperatures (TIT) also offers benefits in turbine blade creep life. This comes in an era where governments and companies have set emissions and noise limits as a key priority in aerospace research [4].

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Water ingestion related to rain suction into a jet engine has been studied [5,6] and since 1998 there have been regulations in place to ensure that engines don't flame out under heavy rain conditions. Rain or runway splash ingestion has a negative effect on engine performance due to possible erosion, and a loss of momentum of the rotating parts due to dropplet impingement, apart from the resulting aerodynamic effects. Film forming on the blades decreases the aerodynamic efficiency of the compressor blade due to the alteration of the geometry and change in blade surface roughness [5]. Roumeliotis et al. [7] indicate that for some cases of rain ingestion, about 60% of the water ingested can remain unevaporated and reach the combustion chamber, causing a decrease in combustor efficiency or even flame-out.

Deliberate compressor water injection, however, is substantially different. The most important difference is that for this approach, atomised droplets of typically small diameters (5–10 μm) are injected into the engine and have been observed to follow the flow path [8–11]. These droplets usually begin to evaporate in the initial/front stages of the compressor that brings about the cooling of the air flow (drop in temperature), increased density and moisture content. This procedure has been studied extensively through compressor analytical methods [11–14], through-flow approach, CFD approach [8,15–18], and experimental investigations [9,19–21] that have mostly focused on stationary gas turbines. For the analytical methods, Kim et al. [22] categorise the models into: natural convection model, diffusion model and Stokes model. The authors conclude that the three models agree with minor differences. The natural convection model is based on detailed droplet thermodynamics and accounts for sensible and latent heat transfers due to natural convection. A detailed analysis using this method is offered by Chaker et al. [23] and subsequently applied by Sanaye and Tahani [24], Zheng et al. [12] and Kim et al. [22].

The diffusion model assumes that the evaporation of the droplets occurs mainly due to mass concentration differences and ignores radiative and convective heat transfers. This approach was chosen as the main mechanism applied in this study, following Chaker et al. [23] conclusions that the droplet temperature will very quickly converge to the saturation temperature, hence the heat transfer term can be neglected. The diffusion model is described further, in a subsequent section. Hill [25] proposes the use of this model to offer a thermodynamic analysis implemented in White and Meacock [11]. Ref. [11] uses the diffusion model to evaluate the compressor operating point changes with water injection using through-flow methods, and proposes an expression for the evaporation rate for equilibrium evaporation. Zheng and Sun [12], subsequently applied these expressions and extend them to a non-ideal case for non-equilibrium evaporation. In the article, wet compression efficiency is defined and inlet fogging is compared to internal intercooling. The investigation gives a comprehensive insight into the thermodynamics of wet compression, but does not provide an expression for the evaporation rate and a constant value is used. The study shows the influence of compressor water injection on the polytropic coefficient of compression, which is smaller than that seen for the "dry" case. The reductions in compression specific work are evaluated and accounted for due to the fact that ideal compression will no longer be adiabatic but will have a heat transfer term due to water evaporation.

In a later investigation, White and Meacock [26] study multi-spool compressors and conclude that multi-spool engines adapt better to water injection due to the extra degree of freedom of the intermediate shafts. The results were confirmed with Bagnoli et al. [7] analytically, whose work is also taken here as the basis for the development of the compressor model. The research is validated against experimental results presented by Utamura et al. [9].

A similar outcome for a single shaft compressor was obtained by Roumeliotis and Mathioudakis [20], where experimental results on a single stage axial flow compressor are provided. Further experimental work was carried out by Favorskii et al. [19]. In the study, the authors note that the compressor specific work is reduced, but the mass flow is increased, giving as a result almost unchanged compressor power requirement for a 1.5% water to air ratio. The experiment is compared to an analytical method with good agreement.

The focus of most of the mentioned studies is the increment of thermal efficiency and power output of a gas turbine. The idea of using compressor water injection for NO_x emission reduction in aircraft was studied by Daggett et al. [3,27], however, the impact of different environmental conditions in combination with water injection ratios have not been evaluated. There are currently no studies in the open literature that investigate different jet engine configurations and their performance changes during compressor water injection. To achieve indicative operating conditions in the engine models, a stand-alone compressor tool has been developed and it is the focus of this first part of the study. The outcomes are set as boundary conditions for the engine models in part 2 of this study. This study thus, is based on previous investigation of the science of water injection, and specifically achieves the following:

- Shows the drop in intermediate Compressor Discharge Temperature (CDT) as a function of water-to-air ratio, droplet size and ambient conditions
- Highlights the changes in temperatures and hence evaporation rates for 2 and 3-spool compressors representative of modern aero-engines
- Evaluates the impact of injection location in the evaporation process and hence reduction in the intermediate CDT

2. Evaporative cooling model

To model a compressor's thermodynamic performance analytically, an estimated axial pressure distribution along the compressor length, an average axial velocity and compressor length are required. The pressure distribution can be obtained by means of Eq.(1), as indicated in Refs. [11,14].

$$P_2 = P_1 e^{ct} \tag{1}$$

where P_1 and P_2 are the inlet and exit stage pressures respectively, c is the compression rate, which according to Refs. [11,14], amounts to 200 s^{-1}, and t is the compression time.

With known flow velocity and axial length of the compressor, one droplet of water can be tracked through the compressor. The droplet absorbs sensible heat from the surrounding gas and uses it as latent heat of evaporation. As the droplets travel and follow the streamlines, they reduce in size and heat up. The surrounding air will be cooled while increasing its humidity or water vapour content.

The mass fraction of water vapour (v) to dry air (a) is known as the specific humidity of air (ω), which can be expressed in terms of the partial pressures of water vapour and dry air. The partial pressure of dry air will be the atmospheric pressure, P, minus the partial pressure of water vapour, P_v,

$$\omega = \frac{M_v}{M_a} = \frac{P_v/R_v}{P_a/R_a} = 0.622\frac{P_v}{P - P_v} \tag{2}$$

If water is added to the dry air, w will increase up to a maximum value after which further addition of water will condense in the air rather than humidify it. The relative humidity of a mixture relates