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PERFORMANCE ANALYSIS OF TWIN-SPOOL WATER INJECTED GAS TURBINES USING ADAPTIVE MODELING

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ABSTRACT

The development of an adaptive performance model for multi-spool gas turbines, equipped with the possibility of water injection is described. The model covers water injection at engine inlet, between the compressors and at the compressor exit. The selection of modification factors and the procedure for adapting component characteristics to overall performance data is discussed. A case of adaptation to overall performances is presented. The use of the model for studying overall engine and components performance is demonstrated. It is shown how operation with water injection modifies component operation, a fact that allows the identification of a wider range of the performance characteristics, in comparison to dry operation. This fact may also increase the diagnostic ability of techniques employing adaptive models. The sensitivity of diagnostic procedures to the different modes of operation of a gas turbine of the type described in the paper is also discussed.

INTRODUCTION

The increasing use of gas turbines in the power generation industry has created an additional incentive for the further improvement of their performances. In the last years several techniques have been proposed for gas turbine power and efficiency augmentation, such as steam or water injection into the air flow or the combustion chamber, with much recent interest in the evaporative gas turbine (Horlock [1]) and the moisture air cycle (Utamura et al. [2]). The fact that gas turbine output and efficiency drop during high ambient temperature periods, when demand usually increases, has led to the broad application of inlet air cooling (Homji et al. [3]).

An answer to the need for more attractive performance characteristics and less dependence on ambient conditions has been given through the introduction of gas turbines with inlet evaporative cooling and intercooling by water spray injection. Aeroderivative gas turbines, in particular, have been used for this purpose. Such gas turbines since their initial introduction in the 1960’s, are at the industrial forefront in terms of simple cycle efficiency. With the introduction of inlet cooling and intercooling, along with water or steam injection at the combustor chamber for NOx control, performance characteristics improve further. Twin spool arrangements are among those that have achieved the best performance characteristics. Although these characteristics make this type of engine very interesting, there is little published for detailed overall engine performance and components behavior. Such information can be obtained with the aid of engine performance models.

Performance models can be further useful for supporting condition monitoring and diagnostics functions. The more complicated layout and the many different modes of operation that can be encountered for these particular gas turbines, imply that condition monitoring methods should be capable for accounting for all different effects. This can be achieved only if the supporting engine models can represent all different types of operation [4]. It is noted here that monitoring systems are widely used today. They provide information which allows an optimal management of engine operation and maintenance and maximizes engine availability.

The present paper describes the procedure for setting up an accurate model of a twin – spool gas turbine, equipped with the possibility for inlet evaporative cooling, intercooling by water injection, and water or steam injection in the combustion chamber. The use of such a model for studying engine performance and components behavior as well supporting diagnostics functions is described.

NOMENCLATURE

C_i	Cooling component with refrigerant power
EXD	Exhaust diffuser
f_i	modification factor
h	Specific enthalpy
HPC	High pressure compressor
HPT	High pressure turbine
HPCD	High pressure compressor exhaust diffuser

HPRT High pressure turbine inlet remix
IV Inlet volute
LPC Low pressure compressor
LPT Low pressure turbine
LPTR Low pressure turbine inlet remix
$\dot{m}$ Mass flow rate
N Rotational spool speed
p Pressure
T Temperature
v Velocity
ρ Density
W. I. Water/Steam injection component

Subscripts

da dry air
v vapour
w water
m air mixture
sat saturated
t stagnation magnitude

CONSTITUTION OF A PERFORMANCE MODEL

An outline of the procedure for building a computer model for a gas turbine and the basic constituents employed for the type of model presented in this paper are described in this section.

Basic Principles of Performance Simulation

In order to build a performance model, a Gas Turbine is viewed as an assembly of different components (modules). Each component is identified according to the kind of process it accomplishes. The working fluid is assumed to be a perfect gas and its thermodynamic properties are interrelated through the compressible flow relations. If $\boldsymbol{Y_{IN}}$ is the vector of independent variables at a component inlet and $\boldsymbol{Y_{OUT}}$ the corresponding vector at its outlet, then in order to find the values at the components exit an equation of the following form must be solved

$$g(\overline{Y}_{IN}, \overline{Y}_{out}) = 0 \qquad (1)$$

This equation usually derives from conservation laws, as well as existing experience in components operation. It can be an analytical relation, possibly including empirical constants (e.g. duct pressure loss), or a set of curves (e.g. turbomachinery component maps). Additional equations express the compatibility between the different components operation. A set of equations which have to be simultaneously satisfied by the fluid parameters, is thus formed. The solution of this system of equations, non-linear in nature, is achieved numerically. Different types of numerical techniques can be employed, as for example described in [5] and by Stamatis et al. [6]. The solution of this system for one operating point gives the full cycle details, and the performance parameters are uniquely defined.

A schematic representation of a twin spool gas turbine of interest to the present paper and its subdivision to individual components is shown in Figure 1. The layout shown has provision for inlet cooling, intercooling, combustion chamber injection and interturbine steam injection.

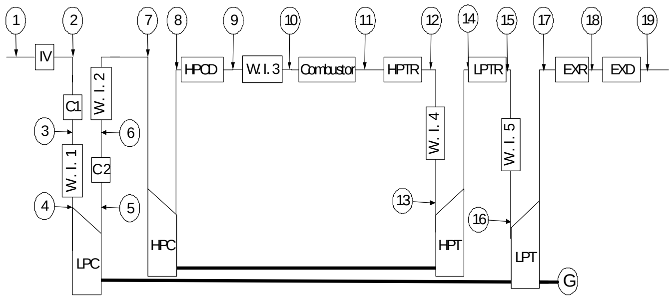


Figure 1: Schematic representation of a twin spool gas turbine and discrimination of its components

Modeling for Water Injection

Gas – Water Mixing: Mixing of gas, namely air or combustion products, with water or steam can take place at different stations along the engine: compressor inlet, between compressors, compressor outlet, between turbines. The way that properties are calculated for mixing at any of these stations is described in Appendix I. In the applications considered in this paper the conditions considered are such that when water is injected, it is always fully evaporated before entering the downstream component.

Turbomachinery Components: The performance maps of each of the engine main components are known with dry air as working medium. The effect of the presence of water vapor is taken into consideration with the use of correction methods reported in AGARD [7] and also discussed by Mathioudakis et al. [8].

Model Adaptation to an Engine

The model described here possesses the ability to adapt to the characteristics of a particular engine. The technique employed for this purpose is the technique of adaptive modeling, introduced by the research group of the authors [9]. The basic idea behind this technique is that component characteristics are allowed to change though appropriate modification factors. The values of these factors are then determined by requiring that available engine performance data are matched by the engine model. The principle of the technique and the particular set of modification factors employed for the gas turbine layout studied here is described in Appendix II.

Modification factors are used for adaptation of an engine model to given performance data during the stage of model building. They can be used as engine health indices, when diagnostic applications are considered.

Model exploitation and handling

Once an adapted engine model has been built, it can be used to support studies of engine behaviour and diagnostics, as mentioned previously. Example applications can be engine operation under different ambient conditions and in different modes of operation (e.g. with or without water injection at various stations, operation with keeping a particular variable constant in different control modes etc). It can also be used to produce sensitivity data, as for example correction curves for different ambient conditions.

In order to have the possibility to perform these operations, the model should be equipped with the ability to operate by setting the values of different parameters, such as Load, CDT, TIT etc. It is also helpful if a user interface facilitating the introduction of different performance parameters and factors is available. The model that has been developed here includes all these features, in a way similar to the model presented in [6].

MODEL IMPLEMENTATION TO AN ENGINE

When the functional relations and solution algorithms constituting a particular engine model have been materialized, the numerical values of a number of parameters have to be defined, as well as the component characteristic maps. We will discuss now how the main such data can be obtained.

Engine Data

The main performance parameters are usually known for the nominal operating conditions of the engine. A piece of information that is of major importance but is usually not available are the performance maps of the main components of the engine. Such data are not published by the manufacturers, while they cannot be found in the open literature, since they usually constitute confidential information proprietary to the OEMs.

In order to constitute a first set of such characteristics one method that can be applied is to use similarity laws and scale maps that have been obtained for components of other engines (as for example discussed by Kurzke [10]), if possible similar to the ones of interest. Several ways of scaling component characteristics have been proposed in the literature, ranging from simple similarity laws (e.g. Saravanamutto et al. [11]) to more sophisticated relations that have been proposed recently by Kurzke et al. [12]. At this stage, if geometric data are available, overall component maps can be constituted from stage performance data, as for example by using adaptive 'stage stacking' methods, as discussed by Tsalavoutas et al. [13].

Adaptation to overall Performance data

Having estimated a set of reference performance characteristics, the application of the adaptive engine model on a number of operating data points can take place. Those points should cover, if possible, a wide range of operating conditions. This procedure will produce a set of modification factors. Incorporating them into the component maps produces a model adapted to the engine under study.

The evaluation of a number of modification factors requires the availability of an equal number of measured variables. The problem that arises at this point is that a limited number of measurements are usually available. The question then is how to employ these measurements in an optimal way for performing model adaptation, either for the initial adaptation to the engine, or for subsequent diagnostic application.

Methods for selecting the sets of modification factors that can be determined from a given set of measurements have been proposed in the past by the group of the authors [14]. If we take the example of a representative twin spool engine, a typical set of measured quantities can be considered to be seven (as for example reported in [15]), which are: Load, fuel flow, N_{low}, N_{high}, T_5, *CDT*, *CDP*, T_{14}, P_{14}. Low pressure shaft speed is assumed constant and Load is selected as control variable. As a result there remain seven of the nine initial measurements. When data at one operating point are available, only seven modification factors can be determined. In order to choose the combinations that can be determined, the method proposed by Kamboukos et al. [14] can be applied. This method provides a criterion for selecting all possible combinations of seven factors, by evaluating the condition number of the corresponding Jacobian matrix. The best combinations (in the sense that they can be evaluated with the highest accuracy from the given data) are those that have the lowest condition numbers. For example, for the set of measurements on the twin spool engine mentioned above, the combination of factors that can be determined with the highest accuracy is the set: f_3, f_4, f_5, f_6, f_7, f_8, f_{10} (eq. B.3 to B.7).

It is noted that a larger number of factors can be derived from a given number of measurements, if data from different operating points are available, applying the principle of 'multi-point' adaptive modeling as described by Stamatis et al. [16].

EXAMPLE APPLICATION TO A GAS TURBINE

In order to demonstrate what can be achieved by the method presented previously, an application to an engine with the layout of a particular commercial gas turbine is presented. Even though measurement data for this engine were not available, a model has been constituted by adaptation to published data by the engine manufacturer. These data are then used to illustrate some operational features of this gas turbine, demonstrating at the same time how the model can be used to derive information that is useful to the engine operator. Although the data presented below do not come from a specific engine, the approach described can be employed for constituting an accurate performance model, if performance data from a particular gas turbine can be obtained.

The gas turbine that will be modeled will have the layout of the LM6000 commercial gas turbine, and the performance model will be adapted to published data for performance of this particular engine.

The quantities of the design point are based on representative values which are published by the manufacturer. The data have been supplemented by quantities evaluated according to the technology level, by published data from previous engines (for example, published information on LM5000, see Burnham et al. [17], can be useful, since the low pressure compressor of the two engines are almost the same), and the rest of the necessary quantities were calculated through a thermodynamic analysis of the cycle at design point. The initial component performance data that are used here are given in **Table 1**.

Table 1: Initial Performance Assumptions

LP Compressor design point		***HP Compressor design point***	
Pressure Ratio	*2.5*	*Pressure Ratio*	*12*
Polytropic Eff.	*89%*	*Polytropic Eff.*	*91%*
$\dot{m}\cdot\sqrt{\theta}/\delta$	*127 kg/sec*	$\dot{m}\cdot\sqrt{\theta}/\delta$	*58 kg/sec*
Stages	*5*	*Stages*	*14*
LP Turbine design point		***HP Turbine design point***	
TIT	*1112 K*	*TIT*	*1469 K*
Pressure Ratio	*7.6*	*Pressure Ratio*	*3.7*
Isentropic Eff.	*87%*	*Isentropic Eff.*	*89%*
$\dot{m}\cdot\sqrt{\theta}/\delta$	*32 kg/s*	$\dot{m}\cdot\sqrt{\theta}/\delta$	*10 kg/s*
Stages	*5*	*Stages*	*2*

Since no published components maps of the engine, or enough data for producing them exist, they were estimated by means of the similarity method, on the basis of the above design point values.

Having estimated a set of reference performance characteristics, the application of the adaptive engine model on the available data takes place in order to obtain a more accurate estimation of the engine performance characteristics.

Model Adaptation

The data used were curves expressing the heat rate of the engine in function of ambient temperature, for a certain load profile, as presented by Organowski [18]. A multipoint adaptation procedure is applied. The curves are digitized and the heat rate values are matched at all different operating points, for dry operation and operation with water and steam injection. The modification factors for compressors and turbines, as well as the amount of bleed flows were considered as unknowns. A schematic of the procedure used is shown in Figure 2.

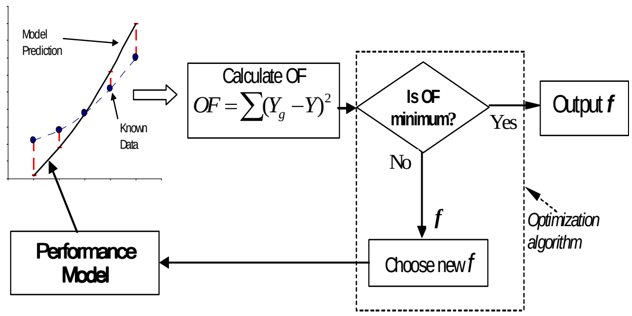


Figure 2: Model adaptation to multiple point performance data.

Some additional information needed for other operation parameters was deduced from other published sources. For example, the amounts of water and steam used were deduced from the levels of emissions specified and other available information relating diluent injection to emissions reduction (Burnham et al. [17] and Pavri et al. ,19]).

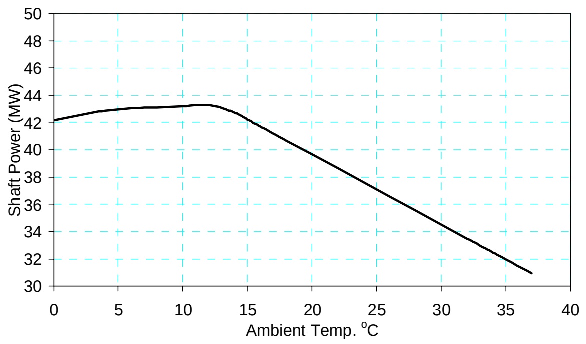
The performances predicted by the model at nominal conditions are presented in Table 2, along with the published data. There is a very good agreement between the simulation and the data at ISO conditions, as it was expected since the initial adaptation was implemented using these data. On the other hand, the predicted off design operation is compared to published values in Figure 3. The load variation of the upper part of the figure is used as the model setting parameter. The heat rate values of the lower part have been calculated and are shown to closely represent the original data used for model adaptation.

We should remark here that although a close agreement to specific performance variables is observed, it is not claimed that the model presented represents accurately the particular gas turbine considered. This would be possible to be done, if additional data were available for this engine, produced for example from measurements. What is demonstrated here is that when some data are available the model can be adapted, to represent them accurately. There are still many degrees of freedom, however, which could be exploited only through availability of additional data to be matched.

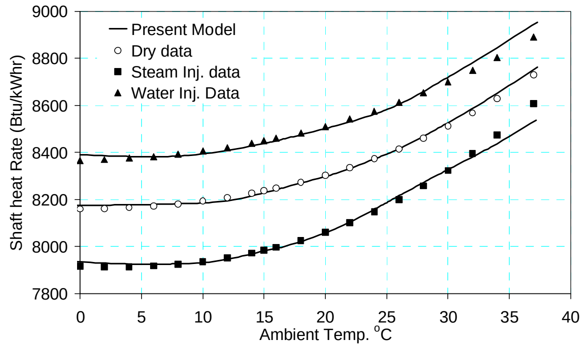
Study of Gas Turbine behavior

Having developed a reliable model with respect to the available data a study of the gas turbine behavior at the cases of concern can be realized.

Table 2: Base Load performance: results of the simulation compared with published data			
	Results of simulation	Data	Δ(%)
Dry operation			
Power (MW)	42.4	42.4	-
Heat rate (Bt/kWhr)	8234.1	8230	0.05
Thermal Efficiency (%)	41.5	41.5	0
Exhaust Temperature (oC)	452	452	0
Exhaust mass flow (kg/s)	125.1	125.2	0.08
Steam Injection operation			
Power (MW)	42.2	42.2	-
Heat rate (Bt/kWhr)	7982.1	7980	0.03
Thermal Efficiency (%)	42.8	42.8	0
Exhaust Temperature (oC)	426.1	426	0.02
Exhaust mass flow (kg/s)	126.9.	127	-0.08
Water Injection operation			
Power (MW)	42.4	42.4	-
Heat rate (Bt/kWhr)	8442.3	8440	0.02
Thermal Efficiency (%)	40.4	40.4	0
Exhaust Temperature (oC)	439.5	440.6	-0.25
Exhaust mass flow (kg/s)	126.1	126	0.08



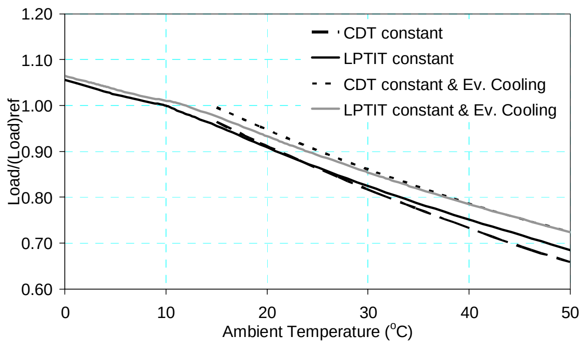
(a) Load



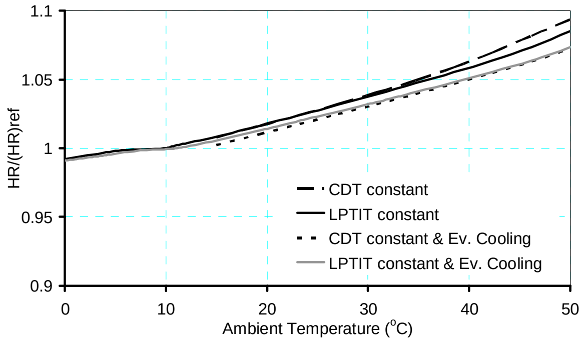
(b) calculation results

Figure 3: Comparison of predictions to data for h eat rate vs. ambient temperature

One operational aspect that can be studied is engine behavior under different control schemes. Such schemes may be rather complicated for this type of engines. The use of different control parameters can be understood by the engine user with the help of the engine simulation program. For example, load variation with keeping compressor discharge temperature or low pressure turbine inlet temperature constant can be derived, as shown in Figure 4a. In the same figure the effect of evaporative inlet cooling is demonstrated for the two modes of operation. The expected trend of output increase with inlet evaporative cooling is observed. A remark that can be made from this chart is that for high ambient temperatures, operation with constant CDT, results in higher gain than with constant LPTIT. The corresponding influence on heat rate is shown in Figure 4b.



(a) Load

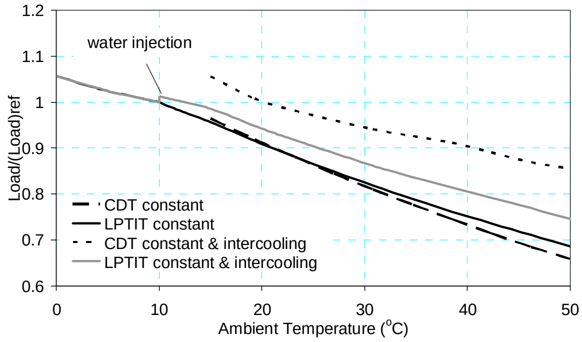


(b) Heat rate

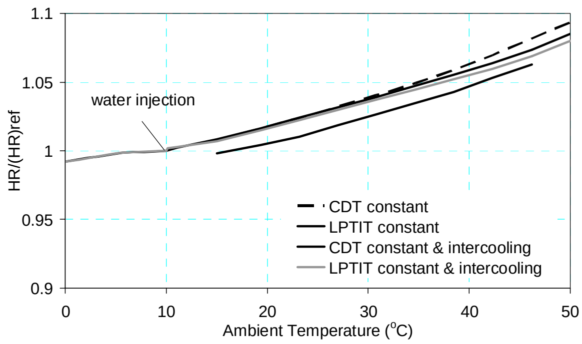
Figure 4: Performance with inlet evaporative cooling for different ambient temperatures.

Similar results for operation with intercooling through water injection between the compressors are shown in Figure 5. In this case the output increase at high inlet temperatures is much larger for operation with constant CDT. The output increase achieved is larger than the one with evaporative inlet cooling. As CDT is the control variable at the ambient temperature region where load is lowered at higher rate, intercooling seems a very promising method for increasing the power of the gas turbine, as it reduces the compressor discharge temperature. To investigate the gas turbine behavior for this particular case, the injection of an amount of water, proportional to compressor inlet temperature was selected according to the values given by Homji et al. [20].

It is obvious that use of a combination of the two modes of operation, evaporative cooling and intercooling will boost performances at an amount that will be the result of the two effects.



(a) Load



(b)Heat Rate

Figure 5: Performance with intercooling for different ambient temperatures.

Components Behavior

It is interesting to examine how the operating point of the different engine components moves for different modes of operation. This is of particular interest for compressors, since change of operating point is desired to be known, especially with respect to the surge line. The interest is that an adequate surge margin is ensured for any type of operation.

The loci of compressor operating points of the Low pressure compressor, for different loads and modes of operation are shown in Figure 6. Since operation for power generation is at constant speed of rotation, operating points for all modes that do not influence inlet condition lie on a constant speed characteristic. The part of this characteristic that is covered for dry operation is extended for operation with steam injection. This means that for obtaining the same power output with steam injection, the engine operates at higher pressure ratios.

If operation of the high pressure compressor is observed, for the same range of operating conditions, Figure 7, it is observed that the operating line moves across several speed lines and is not altered for any other type of operation but with steam injection. When steam is injected, the operating line moves closer to the surge line.

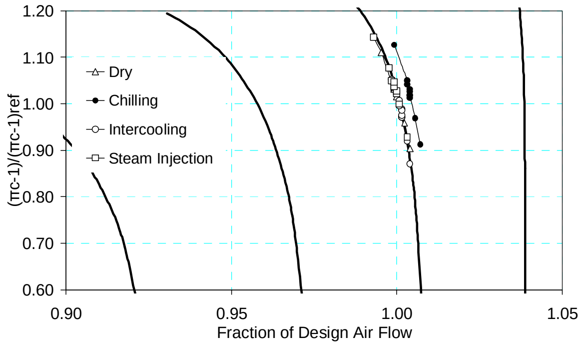


Figure 6: LPC operating point for constant ambient temperature (15°) and Load variant from 30 to 50MW

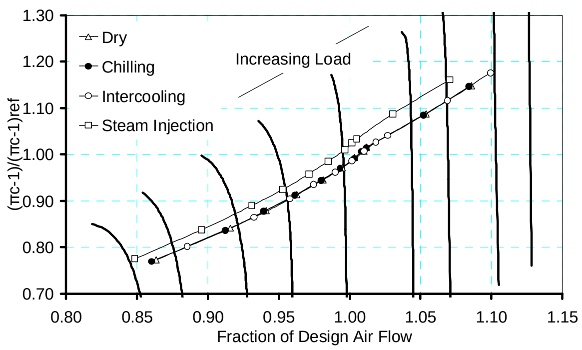


Figure 7: HPC operating point for constant ambient temperature (15°) and Load variable from 30 to 50MW

The movement of operating points on the two compressor maps, for operation with a given output demand at a range of ambient temperatures, for different modes of operation is shown in Figure 8 and Figure 9. A first remark is that when ambient temperature varies, the operating point of the LPC moves across different constant speed lines. This is a result of the fact that the mechanical speed is constant but inlet temperature changes. Thermodynamic speed ($N/\sqrt{T}$) thus changes. Steam injection raises the operating point towards the surge line, while water injection intercooling lowers it .

Observing now operation on the HPC map, a behavior similar to the one noted in Figure 7 is observed. The remark is that now the range of rotational speeds covered is much narrower. For given output demand, HPC operating point changes very little for different modes of operation.

The movement of operating points observed for different modes of operation, wet operation in particular, offers some additional possibility for adaptation of the engine performance maps, compared to dry operation. This is understood from the fact that operating points on both compressors move both across and along constant speed lines, giving thus the possibility for adaptation over a range of operating points. As shown in Figure 10, when adaptation can be performed for different points along a constant speed characteristic, the shape of this characteristic can be reproduced. If only one point is used, then the remaining points will have to be assumed, the simplest way being to perform a simple translation of the characteristic.

The advantage is offered especially for the HPC, which operates along a single operating line, unless steam or water is injected in the combustion chamber.

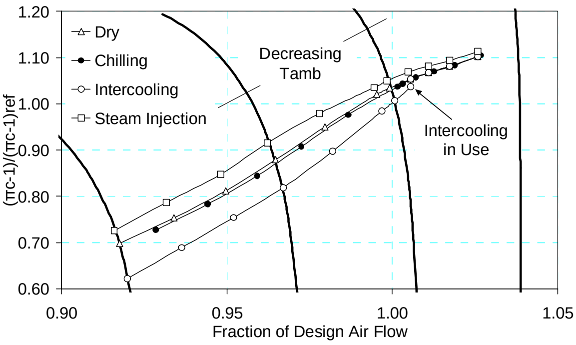


Figure 8: LPC operating point for constant Load (45MW) and ambient temperature variant from -10 to 50^{o}C

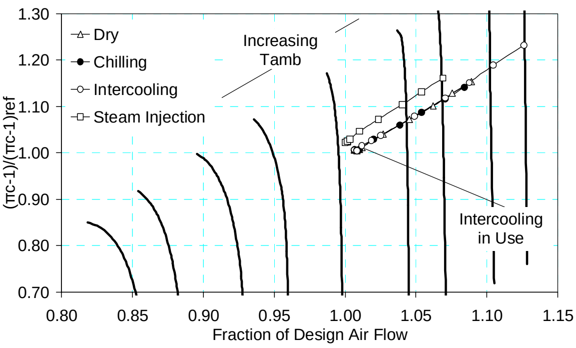


Figure 9: HPC operating point for constant Load (45MW) and CIT variant from -10 to 50^{o}C

Wet Operation and Engine Diagnostics

Monitoring technique based either on direct observation of measured quantities or on parameters derived from them will be influenced by water injection. The water injection results in a change of the operating point of the components; therefore the overall engine performance is modified. The deviations in measured performance parameters caused by water injection will be superimposed to those caused by faults or deterioration of an operating engine. Diagnostic technique based on such parameters may thus lead to erroneous conclusions, unless the effects of water injection are properly incorporated.

An example of a pattern of measurement deviations with respect to dry operation is shown in Figure 11. The existence of such a pattern may have two types of negative effects in a diagnostic procedure: (a) it may overlap with a fault pattern and alter its signature, so that it cannot be recognized, (b) it may mistakenly be taken as a fault. Of course this drawback does not exist if deviations are taken with respect to nominal values produced using an adapted model that accounts for water injection.

The magnitude of changes in measured quantities, caused by injection at the low pressure compressor exit is shown in Figure 12.

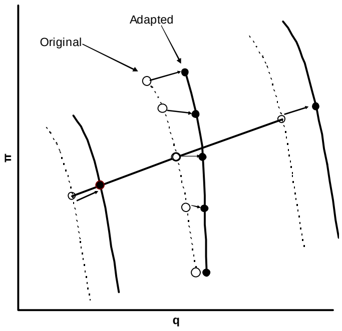


Figure 10: Point-by point, versus single point correspondence for adaptation of constant speed characteristics.

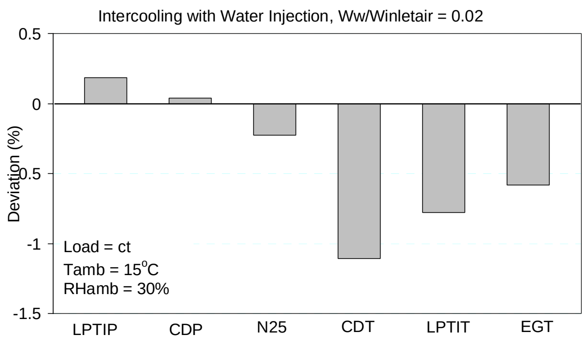


Figure 11: Deviation of measurements for water injection at low pressure compressor exit, with respect to dry operation

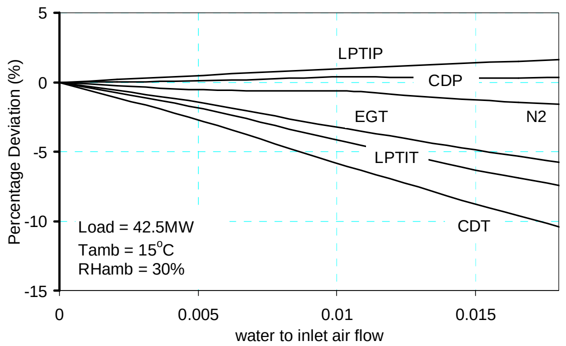


Figure 12:: Percentage change of performance related quantities, in function of water/inlet air flow ratio, when intercooling occurs.

Similarly, when diagnosis is performed by calculating the values of "health indices" from measurement data, unless water injection is properly taken into consideration, then health indices will deviate from their reference values even though no fault is present. An example of modification factor deviations caused by water injection for intercooling is shown in Figure 13. In the case of intercooling and because of the low high pressure compressor inlet temperature, there is a major effect on the health index applied to the low pressure compressor efficiency.

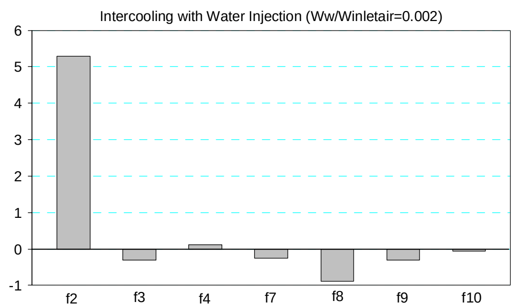


Figure 13: Deviation of modification factors (health indices) if data from operation with intercooling are processed by adaptive model with dry operation

CONCLUSIONS

A method for modeling the performance of twin-spool water injected gas turbines has been presented. The method produces an engine model that is adapted to a particular engine for which data exist. An example of adaptation to specific data available has been given to demonstrate the model's abilities.

It was shown that using this adapted model the performance of the engine can be analysed and the effects of different modes of operation can be assessed. The change of operating conditions of the individual components can also be studied. The way these changes occur, gives the possibility for producing more detailed compressor maps when data from wet operation are available, than it would have been only from dry operation data.

The impact of accurate modelling on performance diagnostics was also discussed and it was shown a model incorporating the possibilities for modelling the different types of wet operation is necessary for continuous reliable engine monitoring.

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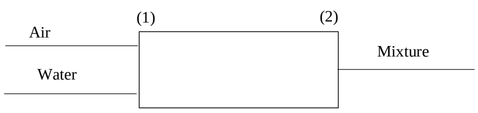
APPENDIX I

Water-Air Mixing Calculation

The flow in the cooling component is assumed to be steady, one dimensional and adiabatic. The droplets partial pressure along with the volume occupied by the droplets is neglected. At cooling component inlet (*station 1*) the thermodynamic conditions of the air mixture and the injected water, are considered known.



Conditions downstream of the cooling component (*station 2*) can be computed through the application of the conservation laws of continuity, energy and momentum which in the case of water injection form the following set of equations:

$$\dot{m}_{da}\left(h_{da1}+\frac{V_1^2}{2}\right)+\dot{m}_{v1}\left(h_{v1}+\frac{V_1^2}{2}\right)+\dot{m}_{w1}h_{w1} - \left[\dot{m}_{da}\left(h_{da2}+\frac{V_2^2}{2}\right)+\dot{m}_{v2}\cdot\left(h_{v2}+\frac{V_2^2}{2}\right)+(\dot{m}_{w1}-(\dot{m}_{v2}-\dot{m}_{v1}))\cdot h_{w2}\right]=0 \quad \text{(A.1)}$$

$$p_1\cdot A_1+\rho_{m1}\cdot(V_1\cos(a_1))^2\cdot A_1=p_2\cdot A_2+\rho_{m2}(V_2\cos(a_1))^2\cdot A_2 \quad \text{(A.2)}$$

$$\rho_{m1}\cdot V_1\cdot\cos(a_1)\cdot A_1=\rho_{m2}\cdot V_2\cos(a_1)\cdot A_2 \quad \text{(A.3)}$$

Dry air enthalpy is a function of temperature while vapour and water enthalpy is a function of both pressure and temperature.

These relations can express the case that no full evaporation occurs, along with the case of possible condensation.

For the needs of the current model and taking into consideration the calculation time (as it is primarily a monitoring/diagnostic model) as well as the fact that the pressure change is small, the used laws are these of conservation of continuity and energy. A cooling component is assumed of constant cross – sectional area.

The non – linear algebraic equations are solved through a numerical procedure, taking into consideration the variation of the composition and the variation of thermodynamic properties of the mixture. The criterion whether saturation occurs is the correlation between vapour partial pressure and vapour saturation pressure at the temperature at component exit. In the case that the mixture is saturated vapour partial pressure is equal to vapour saturation pressure at the same temperature:

$$p_{v2}=p_{sat}(T_2) \quad \text{(A.4)}$$

The constraints of the temperature decrease or the injected amount of water are such to ensure that neither condensation occurs nor water is entering the engine component downstream of the cooler.

APPENDIX II

Elements of Adaptive Modeling

Adaptive Modelling employs the values of measured quantities to determine parameters characteristic to the performance of each gas turbine component, which can in turn be used to assess its health. If a particular component parameter has a value X_{ref} on the reference map and a value X_{act} on the actual "on engine" map, then the relation between the two can be expressed by means of a modification factor f defined as follows:

$$f = X_{act}/X_{ref} \quad \text{(B.1)}$$

(X_{ref} value on the reference map, X_{act} value on the actual "on engine" map). The value of this factor shows how much a particular performance parameter has deviated from its reference value. Given that the occurrence of faults or component deterioration leads to a change of the component performance characteristics, this change reflects on the value of the corresponding modification factor, which can thus be used as a health indicator. Usually, two such factors are defined to describe the health of one engine component.

The values of modification factors for a certain test data set are derived through the following procedure: A component based engine model is used, in which component maps are represented by means of a reference map and corresponding modification factors. For a given operating point the model incorporating the modification factors f_i produces a calculated value for any performance related variable Y_i, for a given set of their values. Each calculated variable $Y_{C,i}$ can therefore be considered to be a function of the vector **f** of modification factors for this operating point: $Y_{C,i} = G(\mathbf{f})$

If a set of measured values for performance related variables $\mathbf{Y_m}$ is available, then we can formulate a cost function CF as follows:

$$\mathrm{CF}(\mathbf{f}) = \sum_i \mathrm{a_i}(Y_{C,i} - Y_{m,i})^2 \qquad \text{(B.2)}$$

The vector **f** can then be calculated so that this cost function is minimized. This is achieved by employing a numerical algorithm for multidimensional optimization, coupled to the engine model, as for example shown in Figure 2.

It should be noted that the sum of equation (B.2) may extend over the individual measurements available at one operating point, but it can also further extend over several different operating points. In this case the method is characterized as "multipoint"

Each rotating component employs two modification factors, one related to pumping (or swallowing) capacity and one related to efficiency. In the case of the combustion chamber, the employed modification factors correspond to the pressure losses and the combustion efficiency. There are also modification factors for the bleed flows, which represent a fraction of the bleed flow. The modification factors used for the twin spool gas turbine are:

Turbomachinery component flow capacity factor

$$f_i = \left(W \cdot \sqrt{T/P}\right) / \left(W \cdot \sqrt{T/P}\right)_{ref},\ i = 1, 3, 7, 9 \qquad \text{(B.3)}$$

where f_1 is used for the low pressure compressor, f_3 for the high pressure compressor, f_7 for the low pressure turbine and f_9 for the high pressure turbine

Turbomachinery component efficiency factor

$$f_i = \eta_p / (\eta_p)_{ref},\ i = 2, 4, 8, 10 \qquad \text{(B.4)}$$

where f_2 is for low pressure compressor, f_4 for high pressure compressor, f_8 for high pressure turbine and f_{10} for low pressure turbine.

Combustor pressure loss factor

$$f_5 = \Delta P_b / \left(\Delta P_b\right)_{ref} \qquad \text{(B.5)}$$

Combustor efficiency factor

$$f_6 = \eta_b / \eta_{bref} \qquad \text{(B.6)}$$

Bleed flow factor

$$f_{bleed} = W_{BD} / W_{BDref} \qquad \text{(B.7)}$$