UNCERTAINTY REDUCTION IN GAS TURBINE PERFORMANCE DIAGNOSTICS BY ACCOUNTING FOR HUMIDITY EFFECTS

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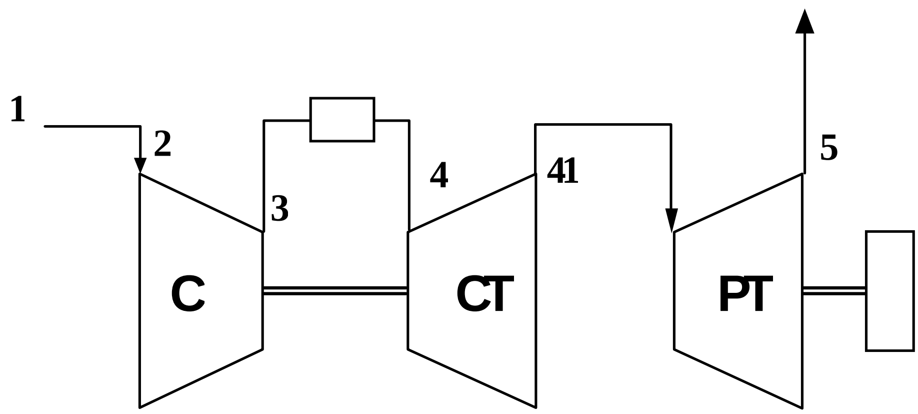
Uncertainty Reduction in Gas Turbine Performance Diagnostics by Accounting for Humidity Effects

- **Modelling humidity effects on gas turbine performance**
- **Impact on Monitoring**
    - **Effects on Measurements**
    - **Effects on "Health Indices"**
- **Demonstration on Test Data**
- **Summary-Conclusions**

Modeling Humidity effects on gas turbine performance

Layout of twin shaft gas turbine, used for constituting a component based performance model.



Working medium: mixture of air and water vapor for calculations of thermodynamic processes

water content: $$war = \frac{m_w}{m_{d,a}}$$

Modeling Humidity effects on gas turbine performance

Component performance parameters transformation

Compressor

$$\left(\frac{N}{\sqrt{T}}\right)_w \Big/ \left(\frac{N}{\sqrt{T}}\right)_d = \sqrt{R_w g_w / R_d \cdot g_d}$$

$$\left(\frac{W\sqrt{T}}{P}\right)_w \Big/ \left(\frac{W\sqrt{T}}{P}\right)_d = \sqrt{R_d \cdot g_w / R_w \cdot g_d}$$

$$\left(\frac{\Delta h}{T}\right)_w \Big/ \left(\frac{\Delta h}{T}\right)_d = R_w \cdot g_w / R_d \cdot g_d$$

Turbines

$$\left(\frac{N}{\sqrt{T}}\right)_w \Big/ \left(\frac{N}{\sqrt{T}}\right)_d = \sqrt{R_w \cdot g_w \cdot (1+g_d) / R_d \cdot g_d \cdot (1+g_w)}$$

$$\left(\frac{W\sqrt{T}}{P}\right)_w \Big/ \left(\frac{W\sqrt{T}}{P}\right)_d = \sqrt{\frac{R_d \cdot g_w}{R_w \cdot g_d}} \cdot \left(\frac{2}{1+g_w}\right)^{\frac{g_w+1}{2\cdot(g_w-1)}} \cdot \left(\frac{1+g_d}{2}\right)^{\frac{g_d+1}{2\cdot(g_d-1)}}$$

$$\left(\frac{\Delta h}{T}\right)_w \Big/ \left(\frac{\Delta h}{T}\right)_d = R_w \cdot g_w \cdot (1+g_d) / R_d \cdot g_d \cdot (1+g_w)$$

Modeling Humidity effects on gas turbine performance

Referred ("Corrected") quantities

Rotational speed: $\boldsymbol{N}_{cor} = \boldsymbol{N} \Big/ \sqrt{\dfrac{g \cdot \boldsymbol{R}}{1.4 \times 287} \cdot q}$

Mass flow rate: $\boldsymbol{W}_{cor} = \dfrac{\boldsymbol{W}}{d} \sqrt{\dfrac{\boldsymbol{R}}{287} \times \dfrac{1.4}{g} \cdot q}$

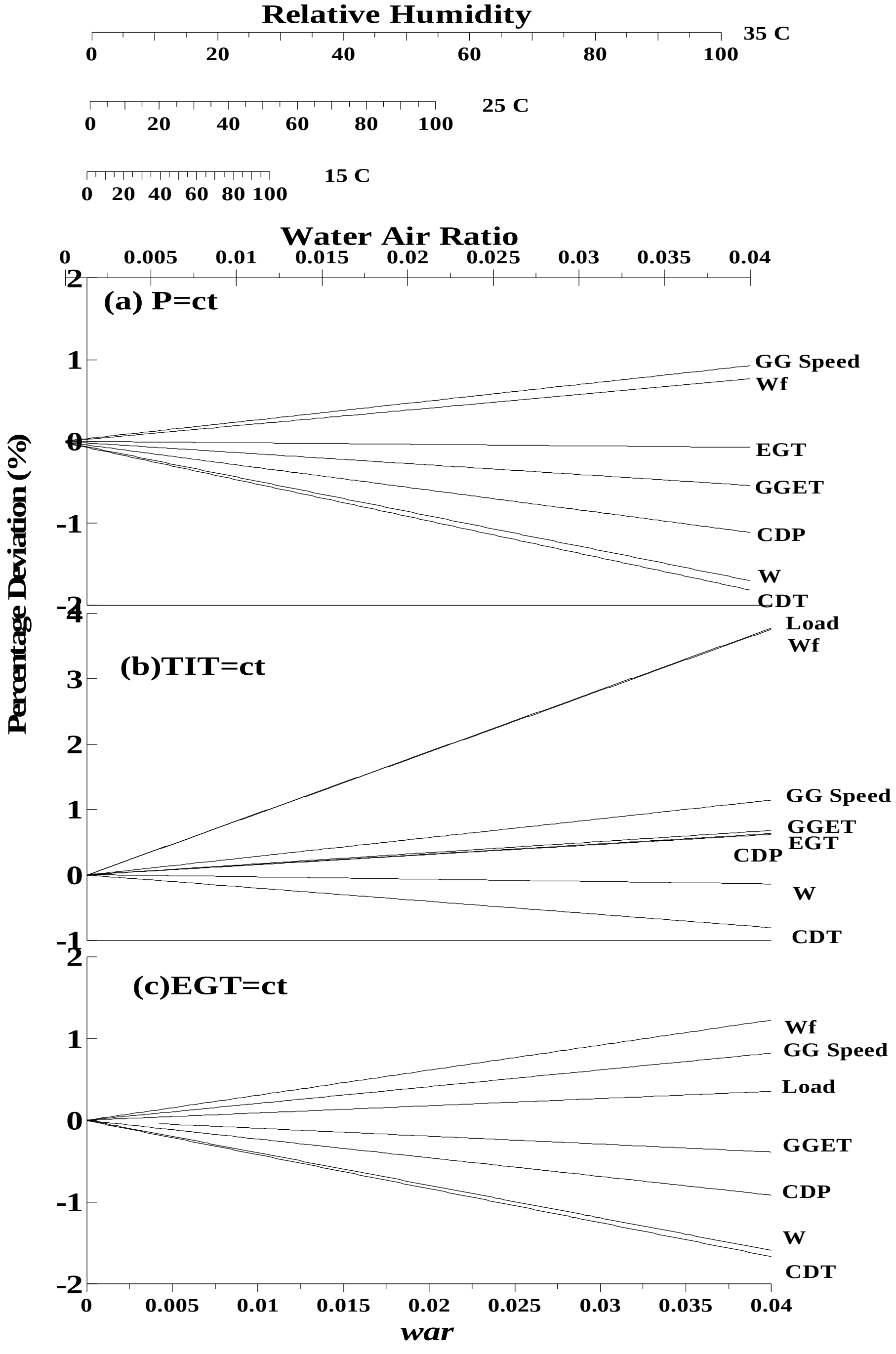
Temperature: $\boldsymbol{T}_{cor} = \boldsymbol{T} / q$

Pressure: $\boldsymbol{p}_{cor} = \left(1 + \dfrac{g - 1}{0,4} \left(\left(\dfrac{\boldsymbol{p}}{d} \right)^{\frac{g-1}{g}} - 1 \right) \right)^{3,5}$

Power: $\boldsymbol{P}_{cor} = \boldsymbol{P} \Big/ \dfrac{g}{1.4} \cdot d \sqrt{\dfrac{g}{1.4} \cdot \dfrac{\boldsymbol{R}}{287} \cdot q}$

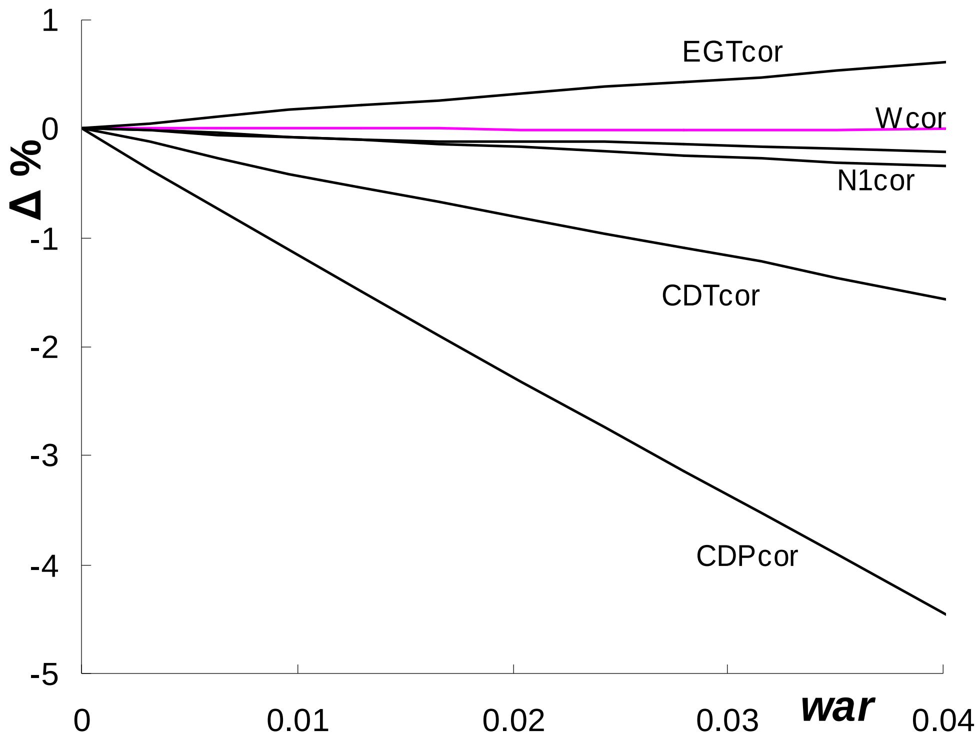
Effect of Humidity on Quantities used for Monitoring

Effect On Measured Quantities



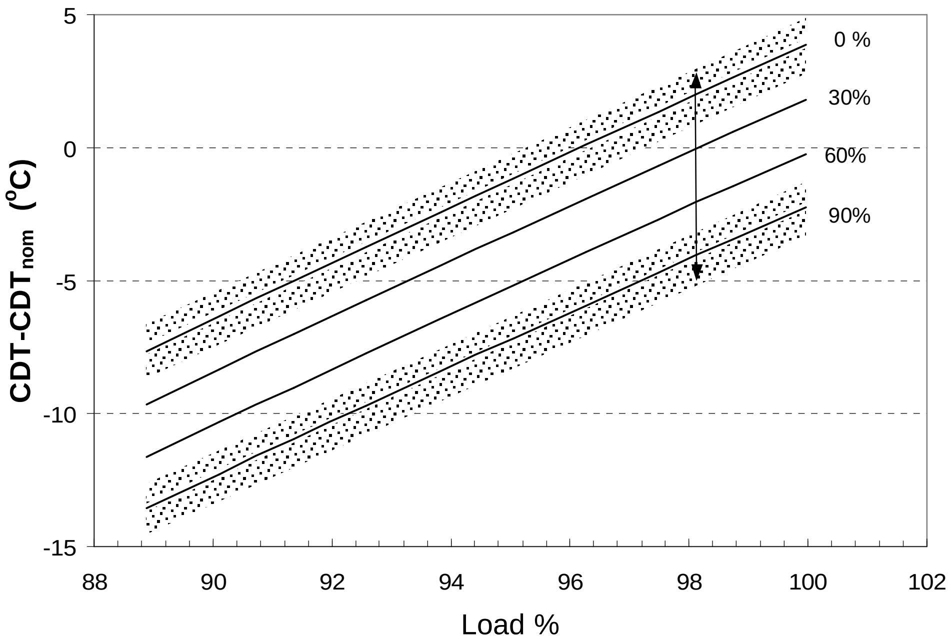
Effect of Humidity on Quantities used for Monitoring

Percentage change of referred quantities for constant referred load.



Compressor delivery temperature - power output

Different relative humidity levels, related uncertainty bands



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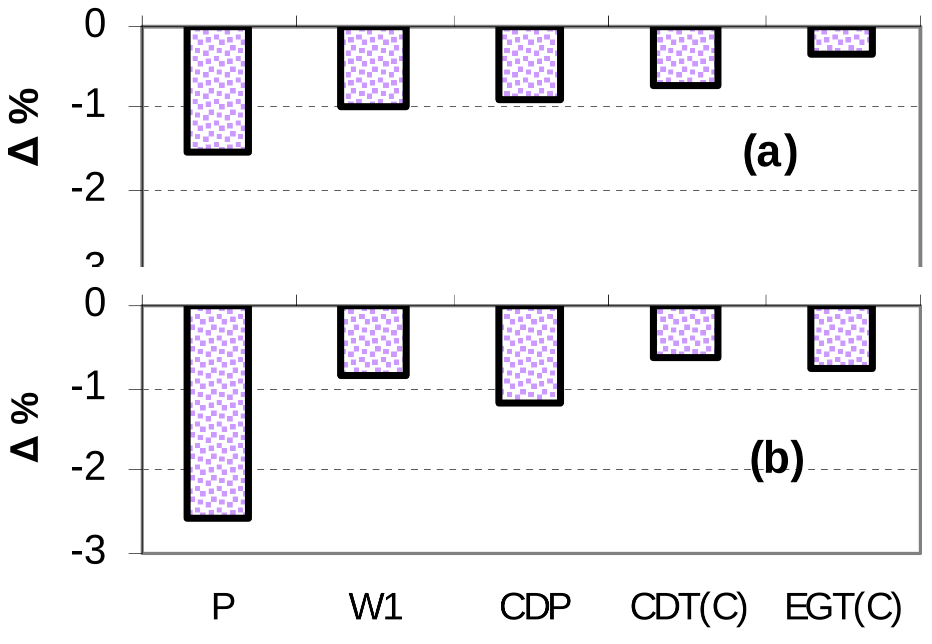
If humidity is not accounted for:

-ability for diagnosing malfunction is reduced, when based on performance quantity interrelations

- changes caused by humidity may be large enough to be misinterpreted as the occurrence of a malfunction, and thus have a false alarm.

Effect of Humidity on Quantities used for Monitoring

Effect on Measurement Deviation Patterns



(a) war=0.009
(b) IGV fault.

Signatures for N1 constant

Effects On Monitored Parameters

Condition assessed using "health indices"

Technique used "ADAPTIVE MODELLING"

Compressor

$$f_1 = \left(W_2\sqrt{T_2}/P_2)\right)/\left(W_2\sqrt{T_2}/P_2\right)_{ref} \quad ,$$

$$f_2 = h_C / h_{C,ref}$$

Gas Generator Turbine

$$f_5 = \left(W_4\sqrt{T_4}/P_4\right)/\left(W_4\sqrt{T_4}/P_4\right)_{ref} \quad ,$$

$$f_6 = h_{GGT} / h_{GGT,ref}$$

Power Turbine

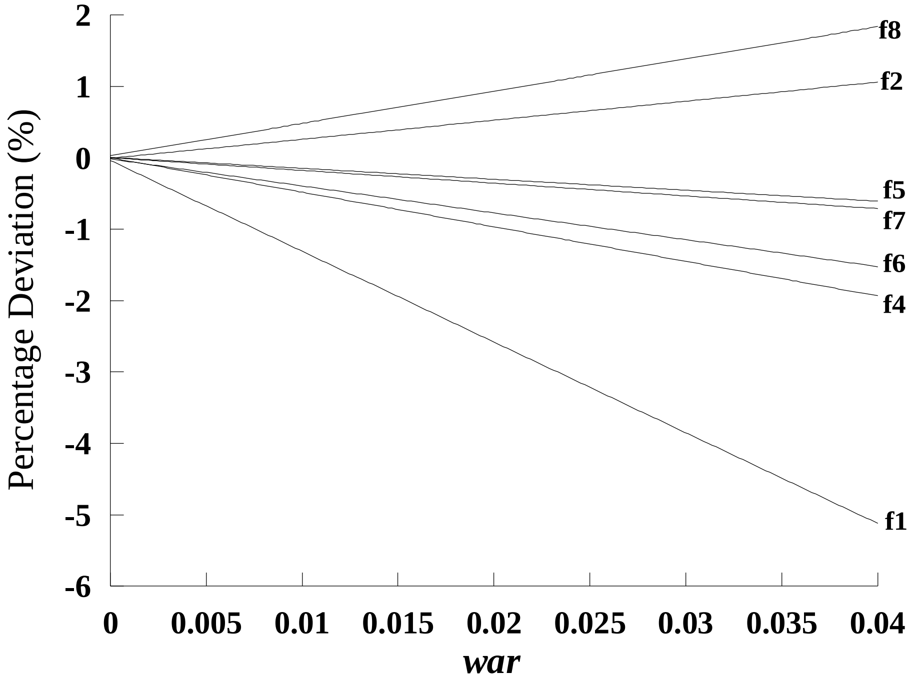
$$f_7 = \left(W_{4.1}\cdot\sqrt{T_{4.1}}/P_{4.1}\right)/\left(W_{4.1}\cdot\sqrt{T_{4.1}}/P_{4.1}\right)_{ref}$$

$$f_8 = h_{PT} / h_{PT,ref}$$

Measurements collected from the engine, fed to the adaptive model, without properly accounting for humidity, produce health parameters different form their nominal values.

Humidity Effect on Component Health Indices

Modification factors deviation, for humid air data processed by dry-air adaptive-model



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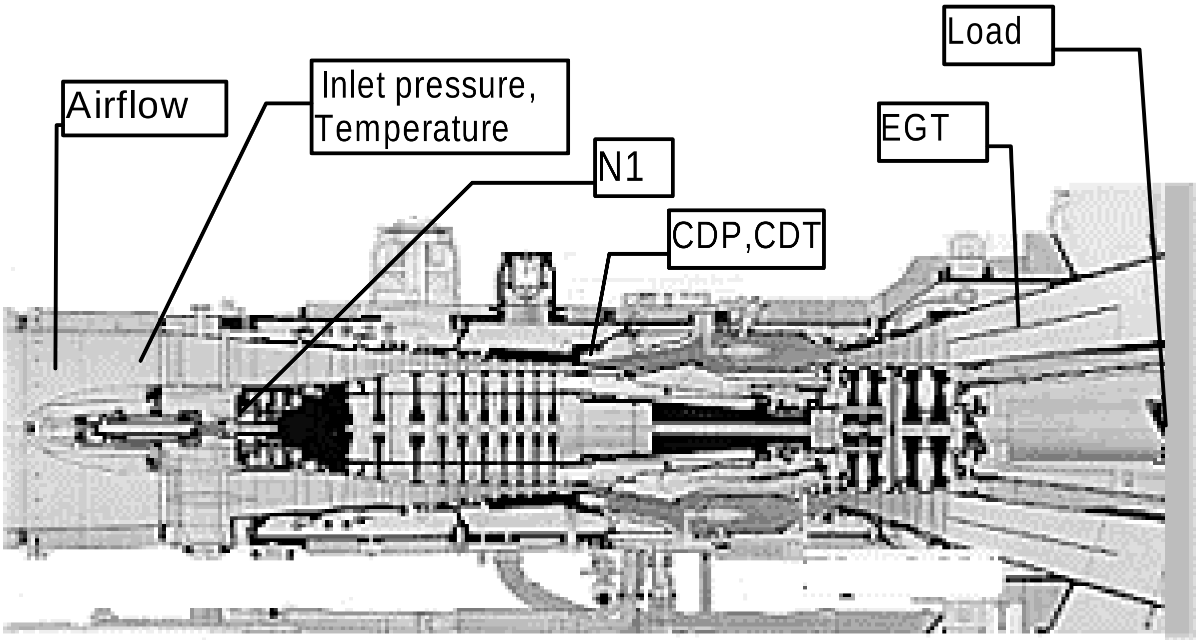
Measurement data from an industrial gas turbine

Layout of gas turbine and quantities measured for monitoring



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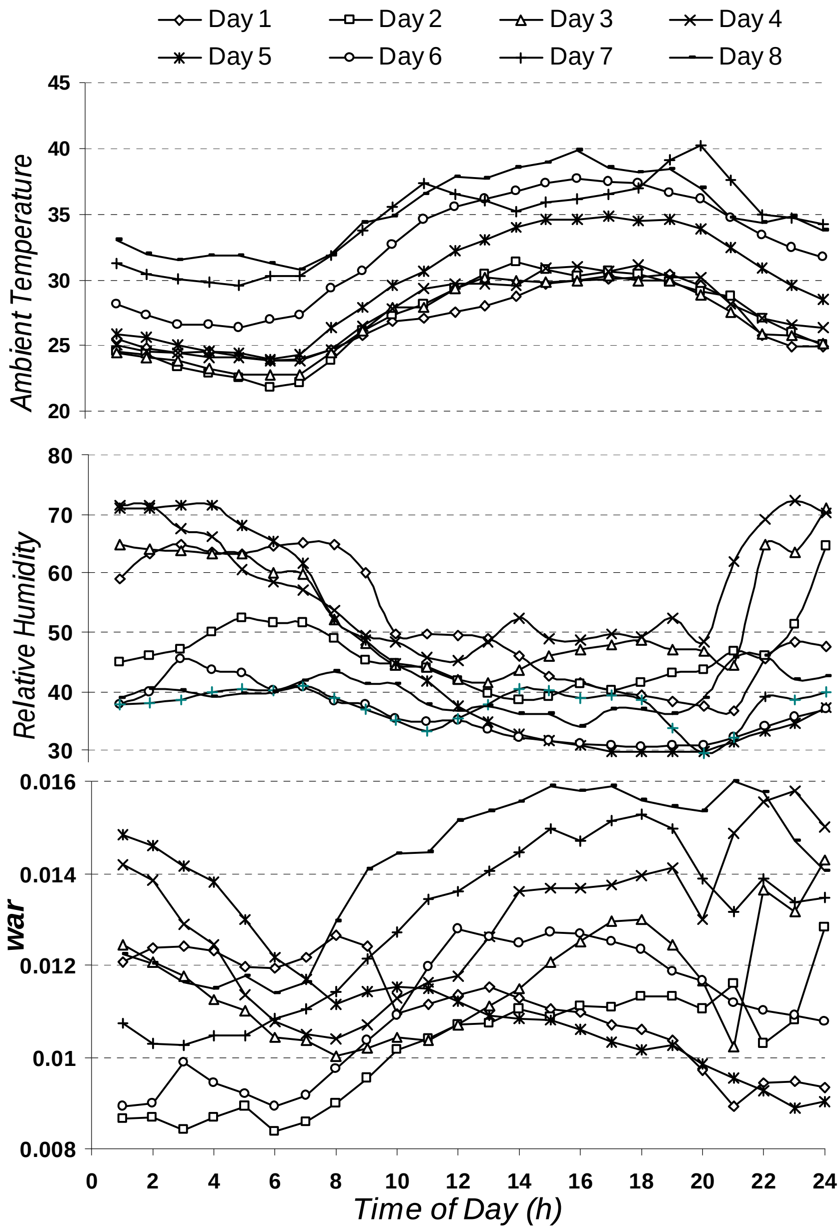
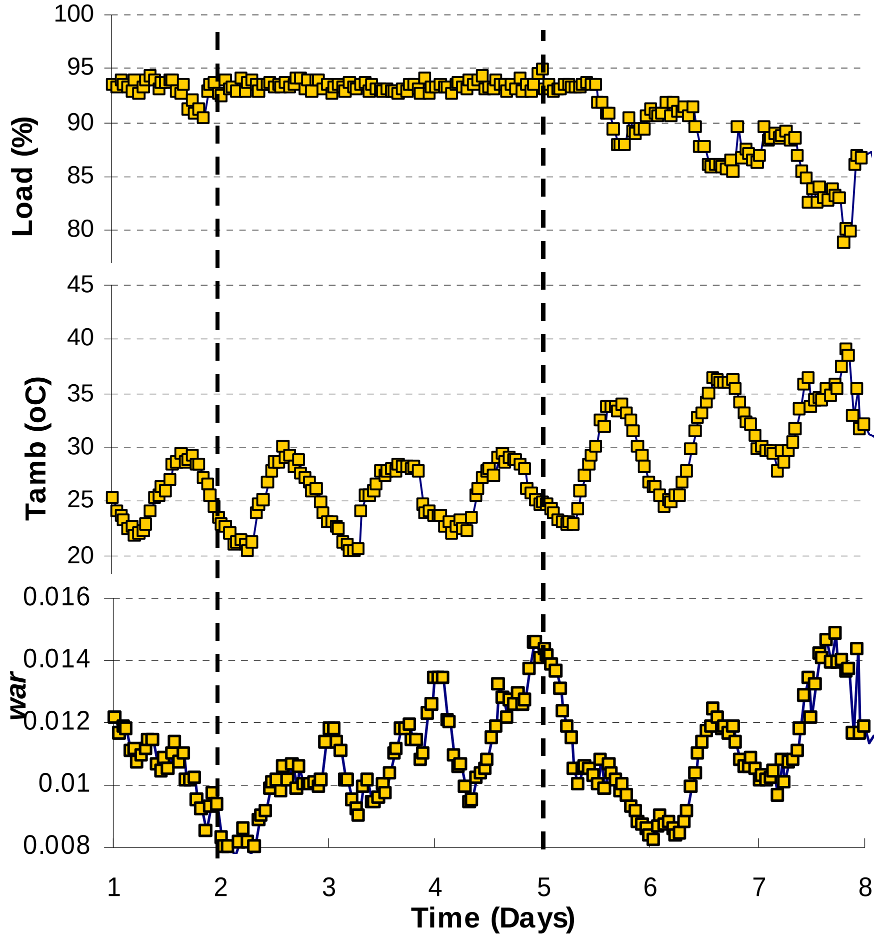
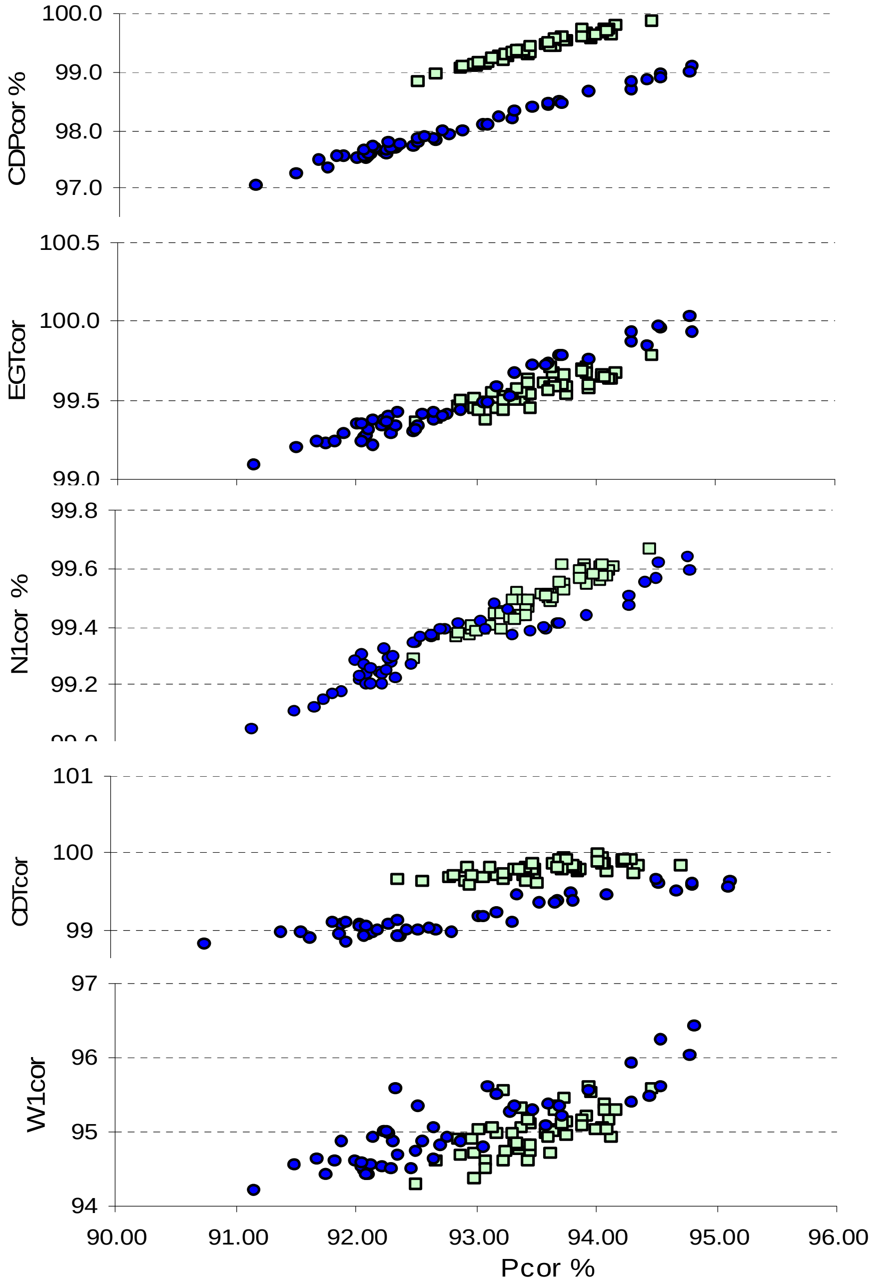
Daily variation of ambient conditions



Variation of ambient conditions over a week



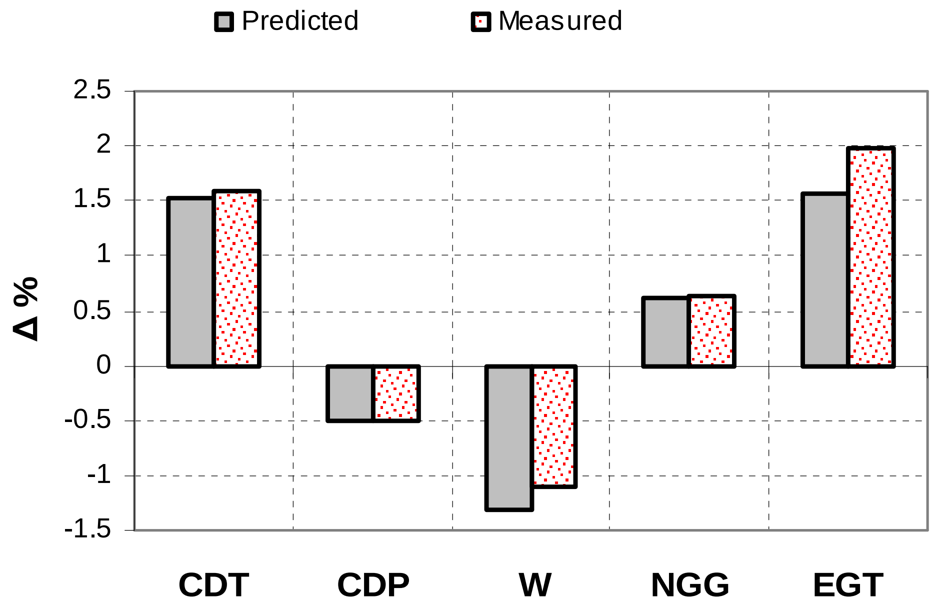
Referred measured quantities for low and high humidity level



Points around Instants A ■ **and B** ●

Estimation of Measurement Deviations

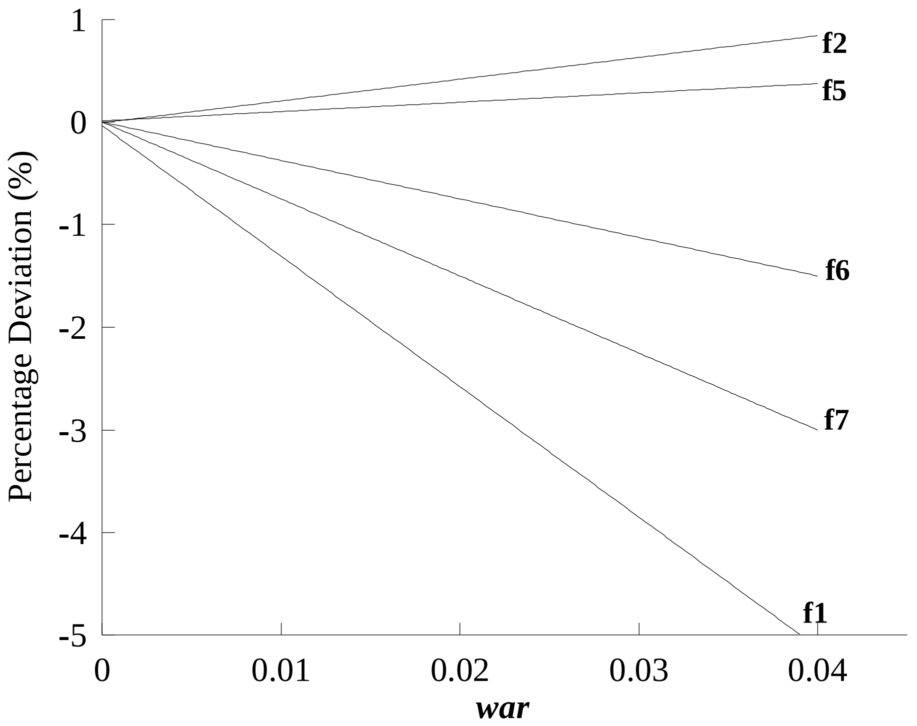
Predicted and measured differences



Comparison of Operating conditions of low(war~0.008) and high ambient humidity (war~0.014)

Health indices deviation for different levels of humidity

Sensitivity of the individual indices to humidity

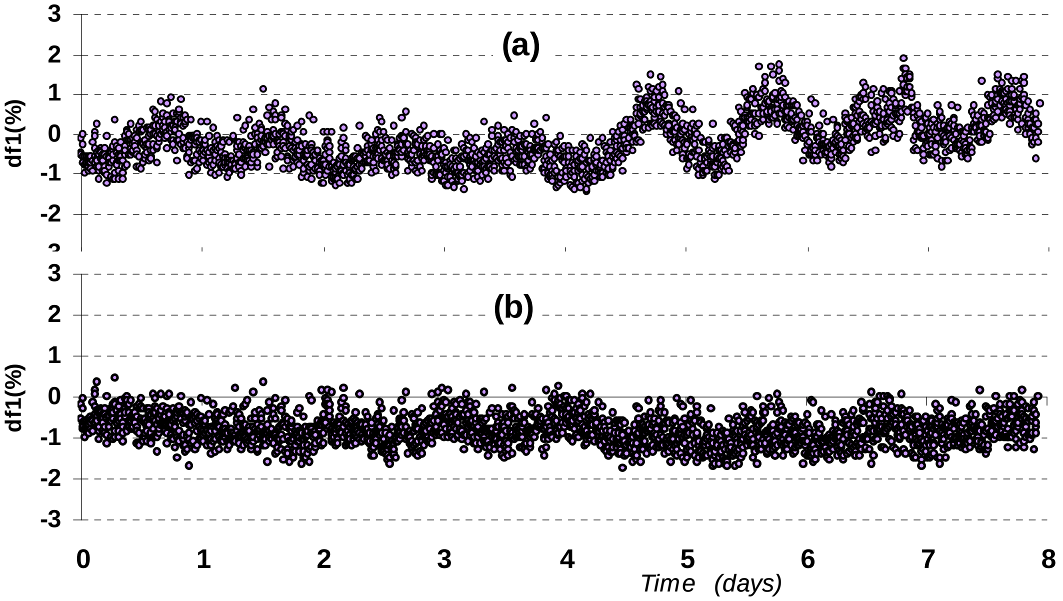


f1,f2,f5,f6,f7 *estimated from N1, CDP, CDT, EGT, W_2*

Indices mostly influenced: f_1 , f_7

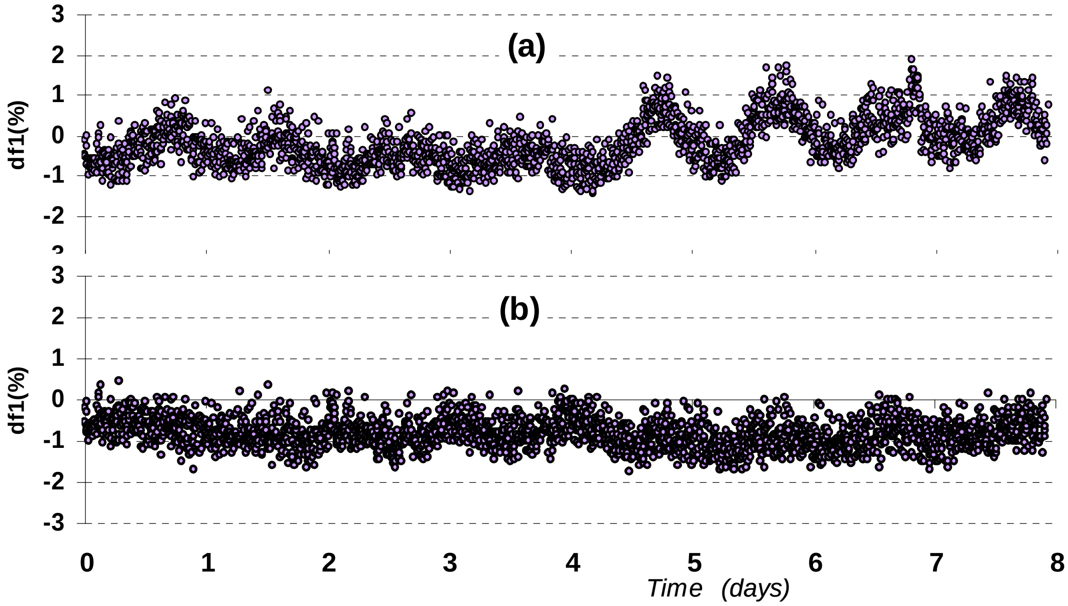
Time evolution of Health-Indices

Compressor flow capacity evolution

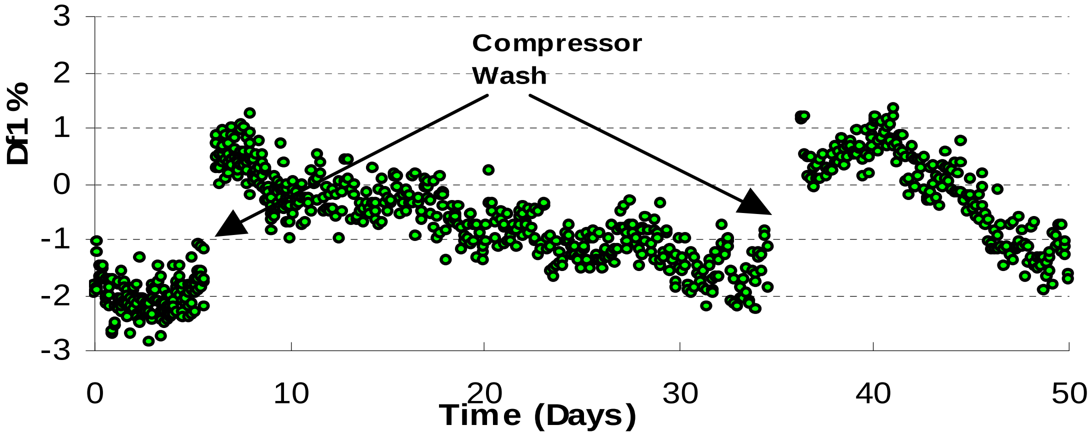


(a) standard humidity of 60%,
(b) actual measured humidity

Humidity induced variation compared to actually expected variations

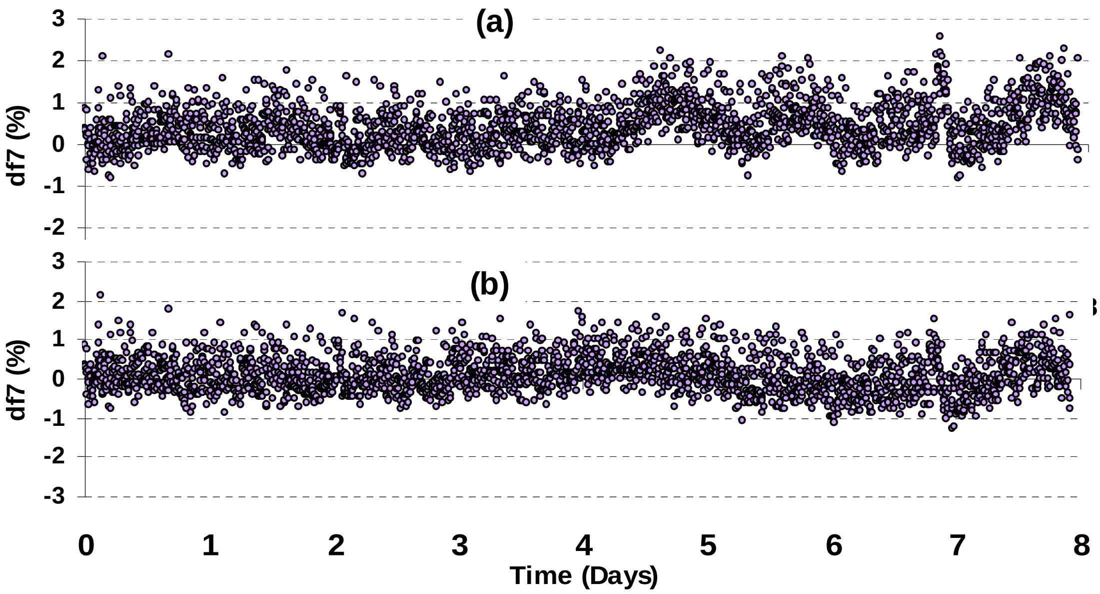


Impact of fouling on Compressor flow capacity, and the effect of compressor wash



Time evolution of Health-Indices

Power turbine swallowing capacity evolution



(a) standard humidity of 60%,
(b) measured humidity

Some Practical Aspects

- *Humidity measurement essential for accurate monitoring*

- *Humidity influence more important when large variations in ambient absolute humidity are expected.*
  - *(This would be the case more for hot and humid climates)*

- *Referred variables to be used for comparing data from different humidity levels.*
  - *The reference condition can be chosen to be representative of an average day, but it does not practically influence the magnitude of observed changes, if it is consistently used.*

- *It is preferable to use the standard absolute humidity for calculations instead of keeping the relative humidity constant or assuming dry air (if a measurement is not available)*

- *Monitoring turbines with inlet humidification requires the support by models incorporating humidity.*

SUMMARY-CONCLUSIONS

- *Effect of humidity on quantities related to gas turbine performance monitoring analyzed. A twin shaft industrial gas turbine was used as a test case.*
- *A method of incorporating humidity effects in an engine performance model described, as well as a method to "refer" measured performance variables*
- *The model was used to demonstrate how measured quantities deviate from their values in operation with dry air.*
- *If humidity is not taken into account, uncertainty bands in measured quantities may be too broad reducing the discriminative ability for diagnostics.*
- *Measurement deviations caused by humidity changes could be of magnitude similar to the magnitude of deviation caused by faults*
- *"Health" parameters exhibit apparent deviations if humidity is not correctly accounted for*
- *Incorporating a measurement of humidity in calculations eliminates apparent trends while it reduces the scattering of "health" parameter values.*