

Coupled modelling of the cooling processes and the induced thermo-corrosive fatigue within a gas turbine

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Abstract: Cooled blades are the critical elements of the hot-gas path components in gas turbines that undergo unpredictable degradation. To better understand damage mechanisms the precise modelling of heat transfer between hot flue gases mainstream, cooling air jet and blades material have been developed, implemented and tested. In particular, an original model of turbulent heat flux responsible for a proper heat transfer has been proposed. Owing a concept of full CFD+CSD coupling, 3D fields of deformation and temperature in the blade has been obtained as a starting data for advanced modelling of degradation: high temperature creep, low cyclic temperature fatigue and hot corrosion. The progress of degradation around a blade hole which appears as a result of exploitation cycles has also been numerically modelled.

1. Modern technology of cooling - motivation

The need of cooling of gas turbine elements that are highly mechanically, chemically and thermally loaded is obvious. Since 1962 when Rolls-Royce launched the Conway – the first engine with cooled turbine blades which to enter into professional service, the cooling technologies have developed, offering significant benefits in terms of mechanical design, turbine performance, life time and cost. Modern research tools as: Computational Fluid Dynamics (CFD) and Computational Solid Dynamics (CSD) are recently used for optimising the blade cooling configurations for maximum efficiency, maximum life time and minimum loss. Also manufacturing techniques are allowing for reduced cooling air requirements.

Presently, there are a lot of advanced cooling technologies such as : convection cooling, impingement cooling, film cooling (fig 1), effusion cooling and hybrid cooling [10]. All of them should combine the high effectiveness of cooling with homogeneous temperature distribution [7-9].

The success of cooling technology and material sciences has lead to appears a family heavy-duty industrial turbines, therefore, the number of gas-turbine-powered hybrid and combined

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plants has been increasing because of their environmental compability, low exergy destruction and high-efficiency. However, several of the hot-gas-path components such as the combustion devices, nozzles and buckets, all operate under particularly severe conditions caused by high gas inlet temperature and frequent start-ups and shutdowns. These specific operating conditions can dramatically affect the life of gas turbine hot section even with permanent cooling protection. An understanding of the original design parameters, actual working parameters and their effect on component life is essential to understanding and modelling degradation modes, especially those resulting from invariable off-design, non-stationary operation [13]. Today, advanced alloy and coating systems are expected to withstand very high temperature, thermal stresses, hot-corrosion attack, thermally induces chemical reactions for periods up to 50 000 hours.

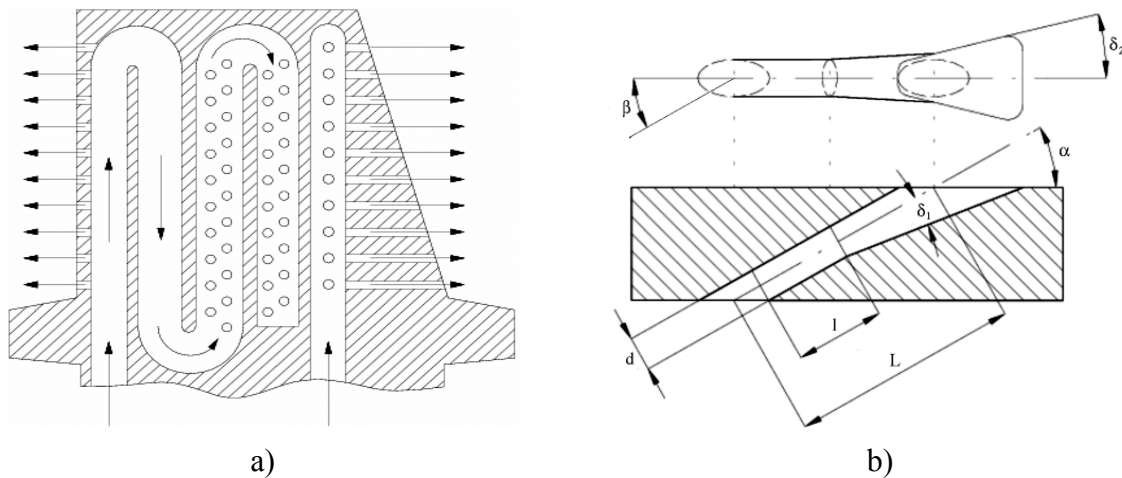


Fig 1. A typical film cooling configuration [1,10]

Steady-state centrifugal stresses range from a few MPa to 300 MPa, while the thermal stresses in the hot-gas path components can range from -400MPa to 700MPa . Typical steady state blade metal temperature range from 750°C to 1000°C depending from the cooling technology. These specific conditions, influenced strongly by unpredictability of cooling, affect the system balance, degradation modes and hence the life. As longer hours of service are accumulated, maintenance consideration such as developing optimum component life strategies and repair process become important. Unexpected changes in physical and chemical microstructure and mechanical ally properties as a result of higher than expected operating temperature stress (due to high temperature gradients) can result in diminished structural performance and consequently reduced life. Such mechanisms like: high temperature growth of carbonitride (creep), high-temperature stress induces recrystalization (early tertiary creep and creep damage), chemical extraction of reaction products (low cyclic thermal fatigue) stress induces hot carbonisation (hot-corrosion damage) have been observed in the first-stage cooled blades in many of advanced engines.

In the paper, there is reported our efforts on a numerical modelling of the turbulent heat transfer from flue gas main-flow into cooled rotor blades coupled with precise numerical modelling of accompanying degradation of blade material. Proposed form of coupling (CFD+CSD) is based on simultaneous solving both sets of governing equations. The first one, describes the compressible hot flue gas and air cooler, the second one, describes a thermo-chemical loading on alloy of a cooled blade. We especially address on novelty of numerical

model of hot fluid flow (chap. 3) and numerical modelling of solid deformation undergoing together with degradation phenomena (chap.5). In particular, an original 3D model for turbulent mechanical flux and turbulent heat flux is developed, implemented and tested [1]. Owing to this model accurate fields of temperature in a blade are calculated, especially a distribution of temperature around a cooling hole. On the other side, for modelling of manifold degradation models within the blade material, an original 3D mathematical model of un-stationary high temperature creep damage, consistent with low-cyclic thermal fatigue and hot corrosion degradation is developed in chap (5).

Since the cooled blades are critical elements of the hot-gas-path, it has been proposed an preventive maintenance system based not only on non-destructive evaluation measurements [20] but also on an original **computational referential state** concept [15]. This *on-line* system can give actual referential data for a health and life management system. Also, after comparing and making corrections with measurement data, the system under discussion may predict deterministically a residual life assessment (chap. 6).

2. Numerical modelling of the blade cooling

The common cooling system (Fig 1) involves many of physical features that can be generally divided into three groups :

- external film cooling connected with proper cladding and smearing of jets of coolant onto a cooled surface,
- internal cooling system with inside blade flow trough mainly ribbed U-bend ducts located inside of blade and connected with external flow via holes,
- intermediate cooling dealing with holes and ducts connecting internal and external flow (Fig 1.). It depends on a surface curvature, shape of hole, its indication and topology of holes manifold [10].

There is difficult to find a one unified mathematical model that will be capable to describe with required accuracy such a plenty of flow phenomena occurring within external, internal and intermediate systems. In thesis [1], it has been elaborated, implemented and tested an combined model for mass, momentum and energy turbulent transport. It undertakes, from very beginning, the problem of the turbulent heat flux \bar{q}^t modelling that in our approach is separately solved from the turbulent momentum flux. Separation of thermal turbulence (θ' -temperature variation) from mechanical one (\bar{v}' - velocity fluctuation) is a fundamental assumption of the model under discussion which means, equivalently, that one has resigned with the standard turbulent Prandtl number assumption [26].

The combined thermo-mechanical turbulence model is based on 9 conservative unknowns $U = \{\rho, \rho\bar{v}, \rho e, \rho k, \rho \varepsilon, \rho(\theta'^2)'', \rho \varepsilon_\theta, \rho(v'^2)'', f\}$ [1]. Last four are a new one, based on the ground of Durbin [24], Deng-Wu-Xi [22] and Abe-Kondoh-Nagano [25] models and denotes: the energy of turbulent temperature fluctuations - $(\theta'^2)''$, the destruction of turbulent temperature energy - ε_θ , the normal turbulence stress $(v'^2)''$, the elliptic relaxation - f .

The turbulent heat flux \bar{q}^t depends now on $(\theta'^2)''$ and ε_θ , which play a role of internal turbulent heat parameters. These are undergo the following evolution equations which have the required conservative form :

$$\partial_t U_q + \text{div}(F^c + F^e)_q = \text{div}(F^v)_q + S_q \quad (2)$$

where the vector of conservative variables U_q , the convective flux F_q^c , the elastic flux F_q^e , the diffusive flux F_q^v , the sources S_q have the form [1];

$$U_q = \begin{Bmatrix} \rho(\theta'^2)'' \\ \rho \varepsilon_\theta \end{Bmatrix}, \quad F_q^c = \begin{Bmatrix} \rho(\theta'^2)'' \vec{v} \\ \rho \varepsilon_\theta \vec{v} \end{Bmatrix}, \quad F_q^e = 0 \quad (3)$$

$$F_q^v = \begin{Bmatrix} (\alpha + \alpha_t(\sigma_{\theta^2})^{-1} \nabla(\theta'^2)'') \\ (\alpha + \alpha_t(\sigma_{\varepsilon_\theta})^{-1} \nabla \varepsilon_\theta \end{Bmatrix}, \quad S_q = \begin{Bmatrix} 2P_\theta - 2\varepsilon_\theta \\ C_{p1}f_{p1}r^2P_\theta - C_{d1}f_{d1}rk\varepsilon_\theta\varepsilon^{-1} - C_{d2}f_{d2}rk \end{Bmatrix} \quad (4)$$

The above model has been implemented to Fluent code [1] and many time tested [1,4,5].

3. Compound cooling modelling

As an example of numerical application of the similar one model that combines two-equation turbulent heat flux closure proposed by Deng et al. [22] and standard RSM second order turbulent momentum flux model, let us consider the Gartshore [21] experiment concerning a single row of round shaped, compound-oriented holes on a flat plate (Fig 2).

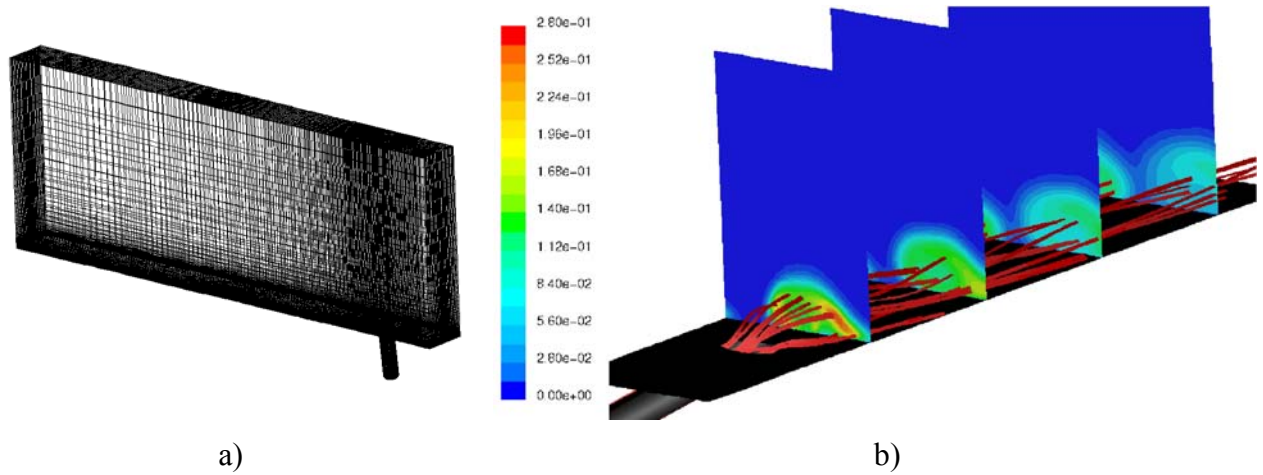


Fig 2. Flat plate cooling configuration [1,4,21]

Three flow cases, by means of the velocity ratio $VR = \frac{V_{jet}}{V_{in}}$ changes, have been considered [1,4]. The detail results of the spanwise distribution of the film cooling effectiveness, that is defined as:

$$\eta = \frac{T_{in} - T}{T_{in} - T_{jet}} \quad (1)$$

where T_{in} - the turbine inlet temperature, T_{jet} - the temperature of coolant and T local temperature on cooled surface, for velocity ratio $VR=1.5$ four particular location of duct cross-section from the coolant injection hole, and four turbulent heat flux closure namely DWX – Deng-Wu-Xi [22], AKN – Abe-Kondoh-Nagano [25], standard constant turbulent Prandtl number $Pr_t=0.85$ and variable Pr_t by means of Kays-Crawford formulae [26] are presented at Fig.3 against the experimental data.

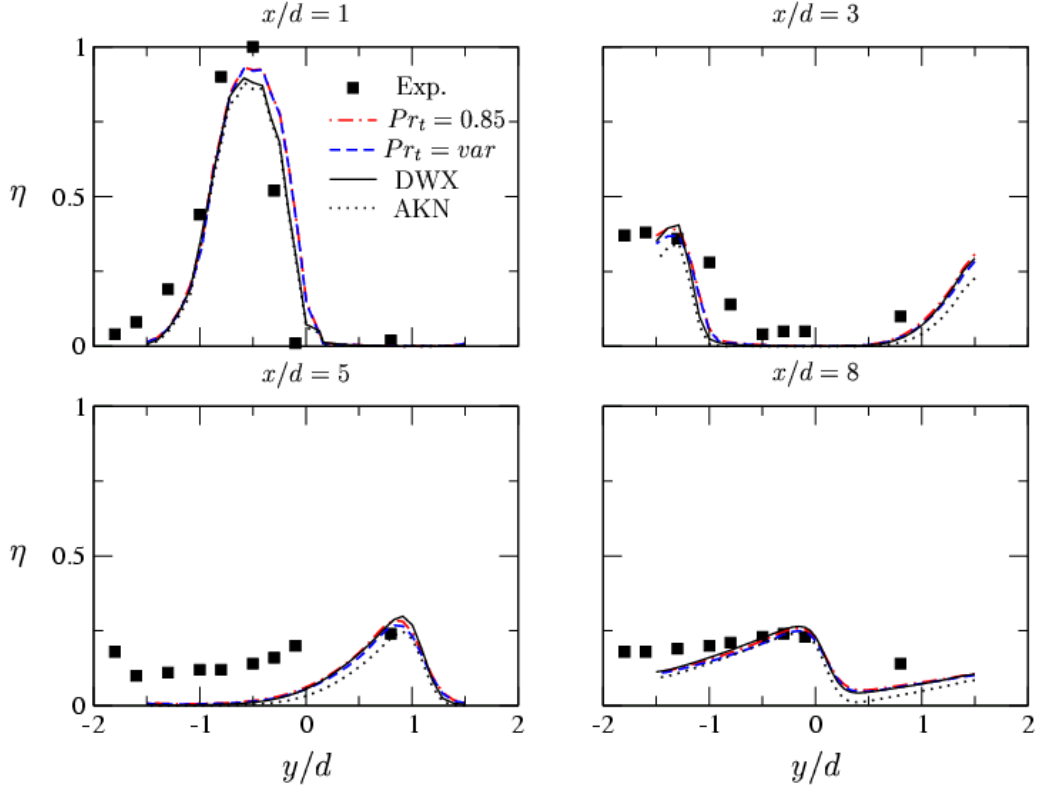


Fig.3. The cooling effectiveness for velocity ratio $VR=1.5$ [1,4]

The contours of cooling effectiveness coefficient η on the protected plate for different velocity ratios are presented at Fig. 4. One can see that the higher coolant jet velocity results in flow separation region in the hole vicinity but on the other hand it makes the distribution of the cooling effectiveness more uniform far from the coolant exit (Fig. 4 b).

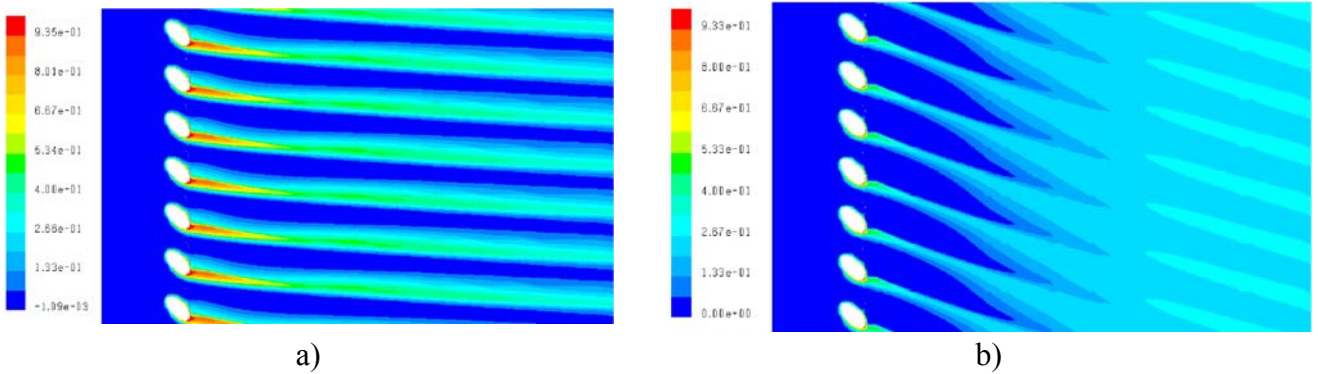


Fig. 4. Distribution of cooling effectiveness on the plate for different velocity ratios
 a) $VR=0.5$ and b) $VR=1.5$ [1,4]

The computed and measured contour of the root-mean-square temperature fluctuation θ'_{rms} defined by formulae:

$$\theta'_{rms} = \frac{\sqrt{\theta'^2}}{(T_{in} - T_{jet})} \quad (1)$$

are presented at Fig.5.

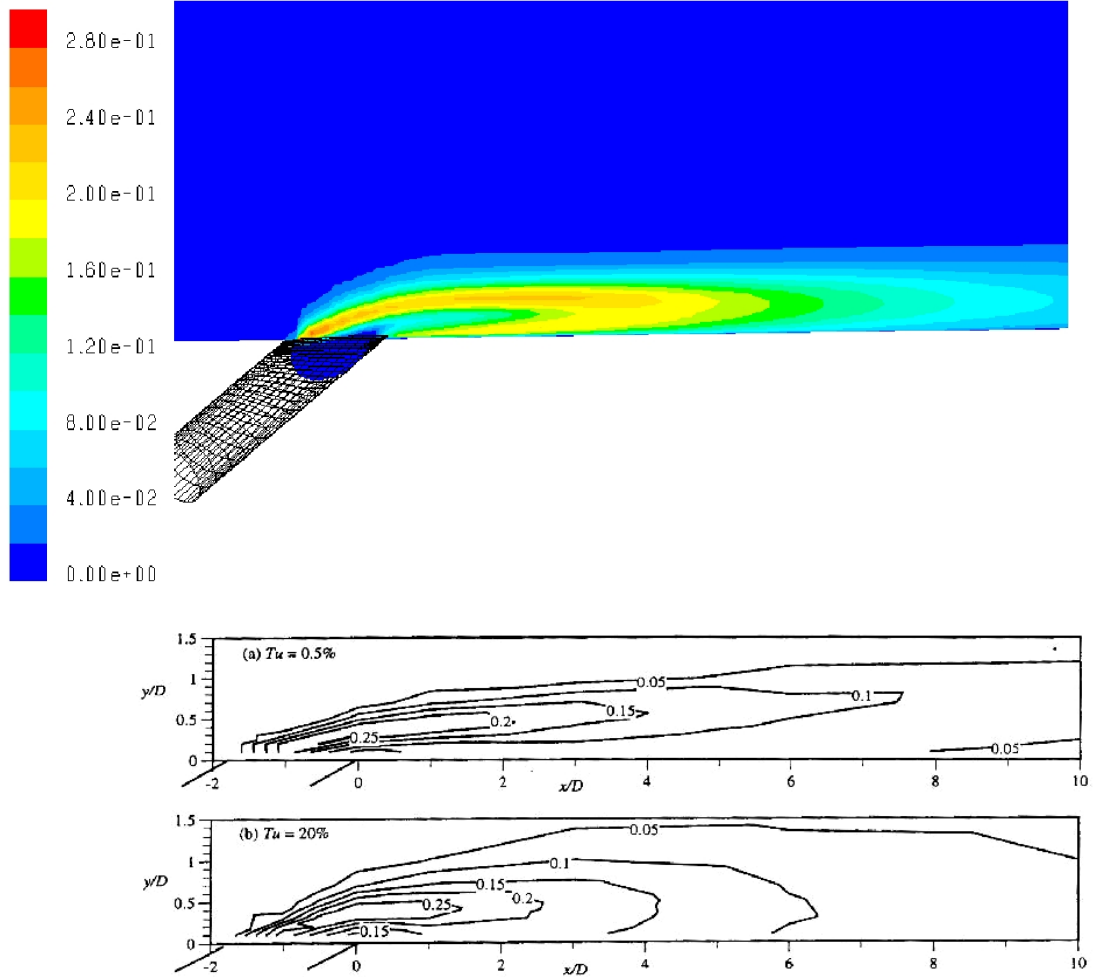


Fig. 5. Contour of rms temperature fluctuations, numerical prediction at upper diagram and below experimental data by Kohli et al. [23]

4. Numerical modelling of material degradation

Single crystal nickel-based super-alloy (CMSX-4, Ni-Flex 120, SMP14) that are usually applied for turbine blades and vanes undergo an extremely high thermal loading. Together with those high temperature it appears degradation connected with apparent irreversible micro-deformations, microstructure changes such as coarsening and coalescence of γ' precipitates, diffusion of chemical reaction products (carbonisation, hydrogenation, oxidation), phase change, super-plasticity, hyper-viscosity, etc. A mathematical model which is capable to describe such complex interactions and related phenomena should be dependent on many internal parameters.

Since all boundary conditions on a solid body are taken from CFD, for full CFD+CSD coupling through mass, momentum and energy equation we need the basic set of governing CSD equations in the conservative, so-called updated lagrangean form :

$$\partial_t U + \text{div}(F^c + F^e) = \text{div}(F^v) + S \quad (5)$$

The set of conservative variables in, our case, consists of 88 unknowns [2]:

$$U = \{\rho, \rho \vec{v}, \rho e, \varepsilon_{ij}^{pl}, \varepsilon_{ij}^{cr}, \varepsilon_{M,ij}^{ph}, \varepsilon_{H,ij}^{diff}, \alpha_{ij}^M, c_H, x_M, \omega\} \quad (6)$$

- where:
- ρ - the density of alloy (1)
 - $\rho \vec{v}$ - the momentum vector (3)
 - ρe - the total energy (1)
 - ε_{ij}^{pl} - the plasticity deformation measure, $i,j = x,y,z$ (6)
 - ε_{ij}^{cr} - the creep deformation measure, (6)
 - $\varepsilon_{M,ij}^{ph}$ - the phasic deformation measure, $M=(ferrite)1,2,3,4,5(martensite)$ (5x6=30)
 - $\varepsilon_{H,ij}^{diff}$ - the diffusive deformation measure , $H= oxygen, hydrogen, carbon$ (3x6=18)
 - α_{ij}^m - the internal evolution parameter $m=pl,cr,ph,diff$ (4x6=24)
 - c_H - the mass concentration (3)
 - x_M - the phase mass fraction (5)
 - ω - the damage progress (1)

Additionally, the convective, elastic, diffusive fluxes are defined to be

$$\begin{aligned} F^c &= U \otimes \vec{v} \\ F^e &= \{\rho v_i, \sigma_{ij}, q_i^e, p_{ijk}^{pl}, p_{ijk}^{cr}, p_{M,ijk}^{ph}, p_{H,ijk}^{diff}, p_{m,ijk}^\alpha, p_{H,i}^c, p_{M,i}^x, p_i^\omega\} \\ F^v &= \{0, \tau_{ij}, q_i^v, J_{ijk}^{pl}, J_{ijk}^{cr}, J_{M,ijk}^{ph}, J_{H,ijk}^{diff}, J_{m,ijk}^\alpha, J_{H,i}^c, J_{M,i}^x, J_i^\omega\} \end{aligned} \quad (7)$$

with 264 (convective), 267 (elastic) and 264 (diffusive) components, respectively.

In the above model all elastic (recoverable) fluxes, denoted by letter p and the diffusive fluxes, denoted in (6) by the capital letter J are obtained using the total energy functional e and the Raleigh dissipative functional D . Firstly the recoverable and irreversible affinities are to be defined, symbolically, as:

$$A^{(re)} = \frac{\delta e}{\delta \alpha} = \frac{\partial e}{\partial \alpha} - \text{div} \left(\frac{\partial e}{\partial \nabla \alpha} \right), \quad A^{(ir)} = \frac{\delta D}{\delta \alpha} = \frac{\partial D}{\partial \alpha} - \text{div} \left(\frac{\partial D}{\partial \nabla \alpha} \right) \quad (8)$$

and next, fluxes recoverable p and diffusive J and sources S are defined :

$$p = \frac{\partial e}{\partial \nabla A^{re}}, \quad J = \frac{\partial D}{\partial \nabla A^{ir}}, \quad S = \frac{\partial e}{\partial A^{re}} + \frac{\partial D}{\partial A^{ir}} \quad (9)$$

5. Numerical evaluation of blade degradation around a cooling hole

Let us consider, as an example both related to M. Karcz's data [1] concerning the distribution of the temperature field and M. Raddatz, I. Martynov's experimental data [12], a single intermediate hole having a simple cylindrical geometry (Fig. 6), loaded by exploitation cycles like: start-up, nominal work, shut-down, stay. Additionally, since we want to obtain a serious (visible) level of degradation only in four exploitation cycles, a weaker alloy P91 is used for constants calibration. The similar calibration has been prepared in Bielecki's thesis [2] and tested onto a few Polish power plants devices [14-17]. In Fig. 6 a point in critical place of internal surface of the hole and the axial cross-section are fixed where temperatures during start-up have been reported (Fig. 7).

For simplicity, only thermal loading has been considered during unsteady state and additionally, a small mechanical tension (0.5 MPa) in x direction was put during nominal work by 1000 hours. In the start-up operation the flue gases temperature growth quickly from 150°C to 1500°C after 0.5 hour. The cooling air temperature is constant in time of start-up and shut-down and is equal 100°C. The bottom surface of the blade keep still uniform temperature that

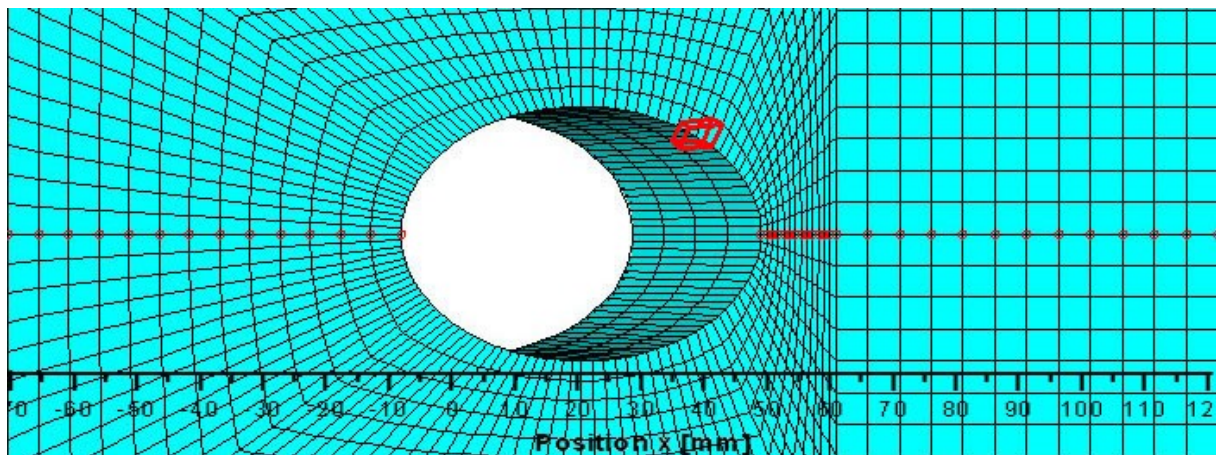


Fig. 6. The geometry of cooling hole

change from 100°C on the beginning of start-up to 700°C on the end of start-up. On Fig. 7 the temperature distribution on the upper surfaces during start-up (6 time increments) is shown, on the left a un-cooled part, on the right – cooled part. In Fig. 9 the progress of thermal stress relaxation and the damage accumulation at the particular point for four exploitation cycles is shown.

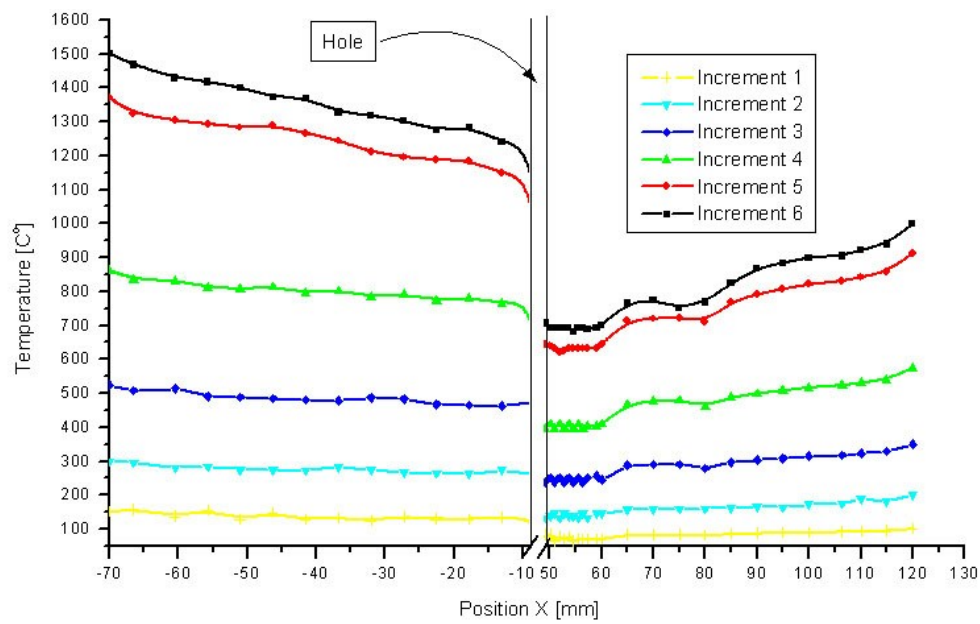


Fig. 7. Upper surface temperature during start-up in the plane of symmetry of the hole

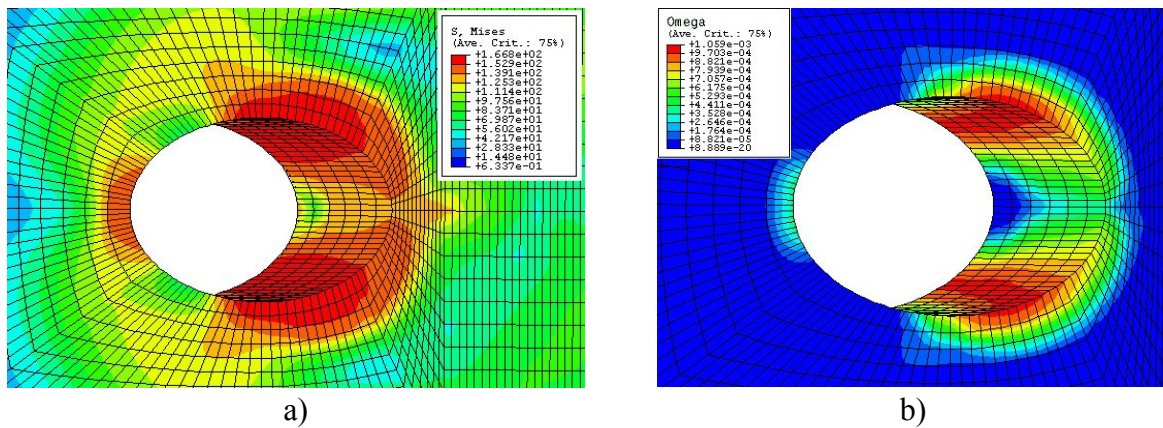


Fig. 8. A view on the degraded domain after of fourth start-up. a) thermal stresses, b) damage parameter

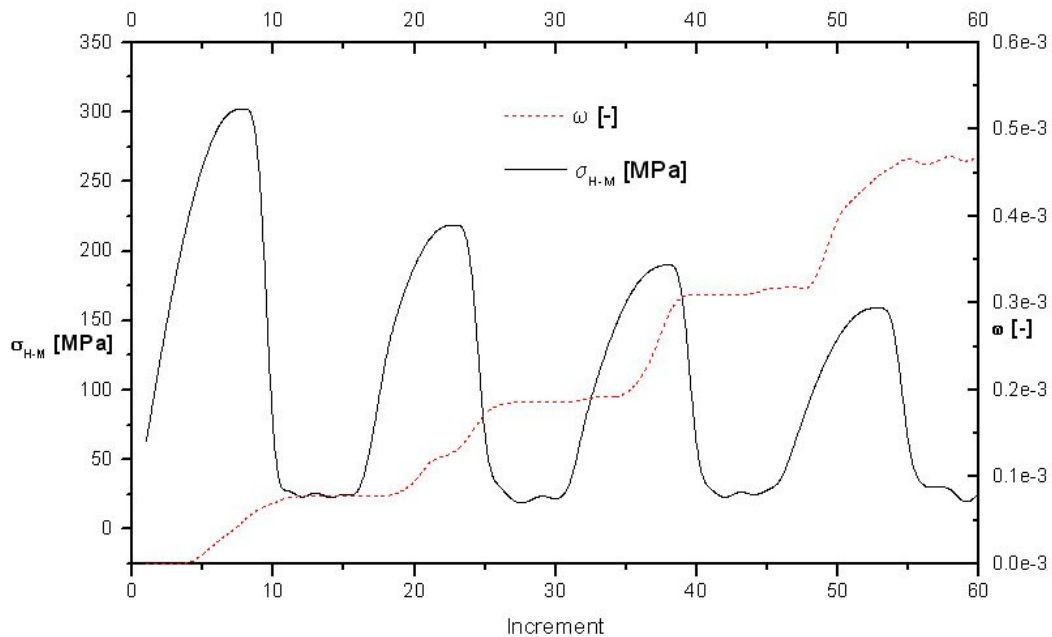


Fig. 9 The progress of thermal stress relaxation and the damage accumulation at the point indicated on Fig 6 during four exploitation cycles.

6. Life management for hot-gas path components of gas turbines

Preventive maintenance of gas turbines is essential in maintaining high reliability during operation, compared to the longer life steam turbines in fossil fuel power plant. For hot-gas-path components two of the preventive maintenance in achieving effective preventive maintenance are residual life assessment and the repair-or-refurbish program. Up to now these procedures are completely based on measurements data taken from non-destructive inspection techniques (using, for instance, signal form ultrasound, eddy current methods, intelligent sensors [19]).

Recently in a few papers [3, 13-16] the authors have proposed an computational technique for obtaining a so-called **computational referential state**. It is based on “on line” calculations every exploitation cycle starting from the first one and taking into account whole history of a turbine. Owing to such computational referential state, a system operator can compare the actual measurement data giving a proper diagnosis concerning health of the turbine hot-path. Having such a correct research tool as the computational referential state, the residual life assessment should be computed easily and the optimal repair-or-refurbish program evaluated.

7. Literature

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