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THE IMPACT OF UNEVENNESS AND INSTABILITY OF FLUE GAS TEMPERATURE ON THE TECHNICAL CONDITION OF GAS TURBINE BLADES

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Abstract

Gas turbines are used in the power sector, aviation, pump houses, and other technical systems. Such a broad range of application is associated with favourable indicators: high power, rather low weight per unit of power, significant efficiency, as well as high durability. All of these indicators greatly depend on the combustion chamber flue gas temperature. It is important for the flue gas temperature to be uniform around the turbine perimeter and stable over time. This condition is extremely important also in the case of frequent temperature variations associated, e.g. with a variable operating range of a manoeuvre aircraft turbojet engine. The paper analyses the causes for the unevenness and instability of combustion chamber flue gas temperature. The impact of the fuel quality, the technical condition of the fuel supply system, as well as the operating conditions of the combustion chamber-turbine assembly was shown. The issues regarding the presence of various types of damage to turbine elements, their blades in particular, were defined. The main cause behind the damage is the unevenness and instability of flue gas temperature, resulting in the presence of overheating, creeping, thermal fatigue, high-temperature corrosion of blade material. The forms of that damage, especially the first turbine stages, were presented. Blade material microstructure test results showed increased layer thickness, grain-size, and especially, adverse modification of the strengthening γ' phase in the temperature function. It was concluded periodic diagnostics of turbine blades with the optical method enables the non-invasive evaluation of their technical condition and drawing conclusions in terms of their durability.

Keywords: *flue gas temperature, gas turbine, blade, diagnostics, technical condition*

1. Introduction

A gas turbine is characterized by many advantages, such as the possibility to achieve high power at small dimensions and small bare weight, a relatively high efficiency of the power conversion process (30-45%), simple design, ease of operation in varying climatic conditions (especially in low temperatures of the surrounding area) and high reliability. These advantages made them find a wide range of application, among other, in the power sector, traction, marine and aviation engines, and in aerospace technologies. Turbine parameters are the better the higher the flue gas temperature downstream of the combustion chamber. A tendency to increase flue gas temperature entails increasing the thermal load on the combustion chamber, as well as the turbine. Currently, depending on the materials the blades are made from and treatments such as cooling or coating the blades with special heat-resistant coatings, the temperature of gas turbine operating medium falls within a range of 1100-1600 K [1, 14]. Turbine operation effectiveness and reliability greatly depends on the operation of the combustion chamber itself. Turbine and jet engines use combustion chambers of various structures: single tubular, multiple tubular, annular, tubular-annular and others [7]. A combustion chamber is given the tasks of completely burning the fuel-air mixture, a rather uniform distribution of the outlet flue gas stream temperature field, combustion stability over a broad operating range, minimum emissions of harmful gases, as well as reliability and durability of functioning over a long-time engine operation [4, 6].

2. Combustion unevenness and instability in the combustion chamber

The fuel combustion process is a complex issue associated with the physical and chemical reaction of the fuel-air mixture. An important role is played by, mainly, the properties responsible for correct spraying and for complete combustion. The most important parameters in this context seem to be the ones associated with the formation of deposits on hot elements of the chamber. These are primarily thermal stability and the content of "present resin" [2, 9]. Both parameters are associated with a set of chemical changes undergoing in the fuel. Resins and thermal degradation products, as high molecular compounds are not sprayed, and as a result, are not completely burned in the engine. As a result of high temperature acting on non-vaporized, relatively high hydrocarbon particles, they undergo thermal degradation, and its products deposit on the injectors and hot engine parts in the form of carbon deposits. It usually leads to the impairment of the fuel-air mixture preparation and intensifies the carbon deposit formation process. In order to prevent loss of combustion stability, special treatments increasing the thermal stability of fuel are used. For example, Fig. 1 shows the impact of an anti-corrosive/lubricant additive (s) and preventing water crystallization (w), and their introduction manner on thermal stability. An additional factor impacting fuel quality change is long-term storage. The presence of microorganisms, which accelerate ageing (thermal and chemical stability is accelerated) is also important, with the decomposition products of biological impurities with mainly acidic reaction (biological corrosion), and dead microorganisms cause filter clogging and problems with supply continuity. The functioning of the injectors impacts the correct spraying of fuel (Fig. 2) [13]. These anomalies have a significant impact on correct combustion, and the correct location of the combustion zone in the flame tube, in particular. Single-sided deposition of coal deposits causes fuel spraying toward the flame tube wall. As a result, a flue gas stream with significantly lower temperature than the average value flows from the flame tube. Otherwise, when the carbon deposit on the injector is deposited along the injector perimeter, the injector supplies fuel in the form of a stream and the combustion area dangerously extends towards the turbine. As a result, a flue gas stream with significantly higher temperature than the average value flows from the flame tube. In consequence, incorrect operation of the injectors impacts the peripheral unevenness of the flue gas temperature field upstream of the turbine.

It should be noted that apart from the temperature changes in the combustion chamber outlet section, there are also local changes of the flue gas stream velocity and pressure. Therefore, the average temperature downstream of the combustion chamber is the mass temperature, which can be expressed with a relationship [4]:

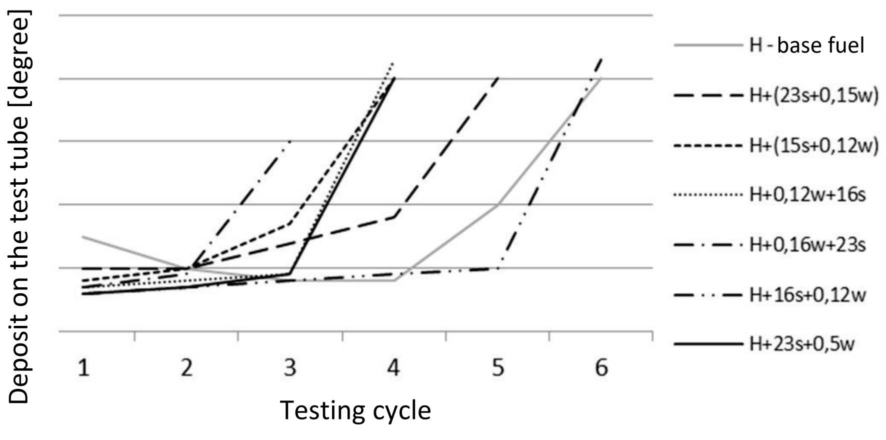

Fig. 1. Results of the test measuring the impact of additive dosage technology on fuel thermal stability (H – means hydro raffinate-based fuel, 15 s, 16 s, 23 s – content of additive s in mg/kg, 0.12 w, 0.15 w, 0.16 w, 0.5 w – content of additive in %(V/V), parenthesis means that the additives were added simultaneously, in the absence of the parenthesis – additives were introduces successively, a week apart) [2]

Fig. 2. Condition of fuel injectors and glow tube: a) carbon deposit along the perimeter, b) single-sided carbon deposit, c) burnout of glow tube

$$T_{3m} = \frac{1}{m_g} \int_A T_3 \, dm_g, \tag{1}$$

where:

dm_g – local flux of flue gas mass measured towards the combustion chamber axis.

The so-called flue gas mean mass temperature is of significant importance to the values of the engine thrust, heat resistance, high-temperature creep resistance of the combustion chamber flame tube and gas turbine blades. The unevenness of this temperature is expressed by a temperature field unevenness coefficient [9]:

$$\text{PF} = \frac{T_{max} - T_3}{T_3 - T_2}, \tag{2}$$

where:

T_{max} – maximum recorded temperature,

T_3 – average temperature of inlet air,

T_2 – average temperature of the combustion chamber outlet flue gas.

An example of a temperature field peripheral distribution in the outlet nozzle of a K-16 engine is shown in Fig. 3. In reality, the flue gas stream exiting the chamber is characterised not only by peripheral uniformity of the temperature field in the combustion outlet section but also the radial non-uniformity of flue gas temperature and pressure (Fig. 4). Therefore, a flue gas stream exiting the chamber is peripherally and radially non-uniform. This last parameter is called the averaged flue gas temperature profile along the turbine blades height. The value characterizing the profile temperature distribution is the so-called temperature non-uniformity profile coefficient [9]:

$$\text{RTDF} = \frac{T_{śr\ ob} - T_3}{T_3 - T_2}, \tag{3}$$

where:

$T_{śr\ ob.}$ – maximum temperature value average along the perimeter.

Examples of flue gas temperature distribution radial profiles for an annular combustion chamber upstream and downstream of the turbine and their impact on the distribution of temperature in the blade material are shown in fig. 3. The peripheral and radial temperature profiles adversely influence the reliability of the combustion chamber and the turbine. [4, 8, 9]. Based on analyses of the studies [4-6] and the operation of turbine engines, it can be concluded that:

- non-uniformity of the flue gas temperature field in the combustion chamber outlet section is present at all operating ranges (rpm) of the engine,
- lack of temperature field distribution repeatability at a specified operating range, moreover, the distribution of this field changes depending on the operating range,
- even with a constant operating range, there is still a significant difference of mean temperatures, along the perimeter, as well as along the radius of the combustion chamber cross-section.

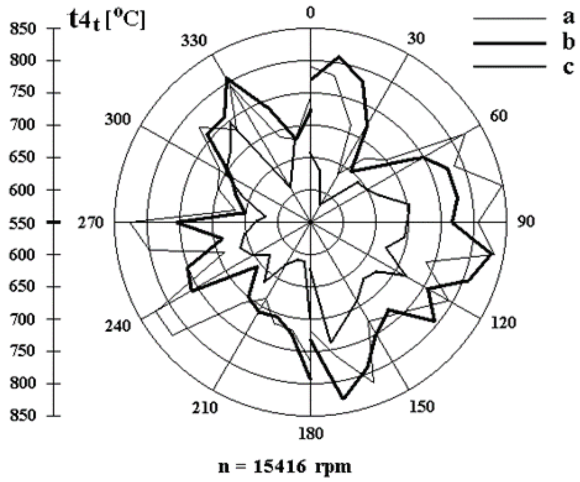

Fig. 3. Example results for measurements of the temperature field non-homogeneity within the working agent inside the jet nozzle of the K-16 engine: a – nearby the outer wall, b – in the middle of the gas duct radius c – nearby the inner wall [14]

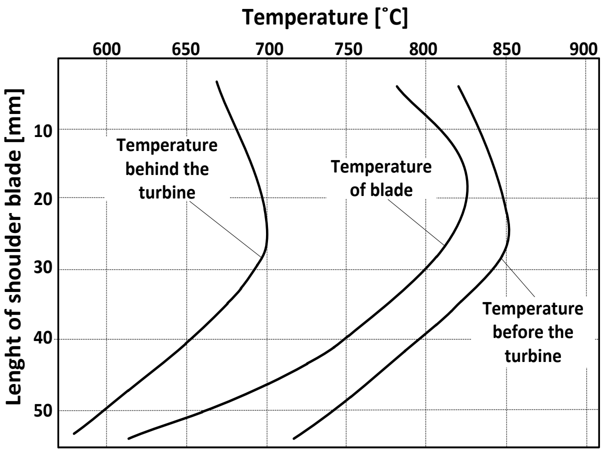

Fig. 4. Examples of flue gas temperature distribution radial profiles for an annular combustion chamber upstream and downstream of the turbine and their impact on the distribution of temperature in the blade material [9]

Moreover, it can be concluded that the magnitude of this unevenness depends, among others, on [6]:
– engine operating range,
– primary and secondary air ratio,
– air excess coefficient values,
– fuel injection system efficiency,
– thermal deformation of the chamber and its elements.

The combustion chamber is also a source of self-excited combustion product stream vibrations, resulting from kinetic [11], aerodynamic and chemical reactions of this process. An important source of low frequency pulsations are fuel system fuel stream pulsations, which, when meeting the condition (5) may cause fuel stream pulsations in the combustion chamber [4].

$$t_0 + t_{ks} + t_{up} \approx k\frac{\tau}{2}, \tag{4}$$

where:
t_0 – combustion process delay time,
t_{ks} – combustion process duration,
t_{up} – fuel system time constant,
τ – vibration period, k – 1, 2, ...

The combustion in the chamber undergoes within a flow with intensive turbulence. It depends on the physico-chemical and hydrodynamic parameters of the fuel-air mixture. Vibratory combustion may appear in the event the fuel stream pulsation frequency is given with the acoustic frequency of combustion chamber vibrations. This is why, adequate fuel stream pulsation limiting glands shall be used within the fuel system [2]. The tendency to vibratory combustion also depends on the fuel injection system. Using a single injector may impact vibratory combustion. A more beneficial structural solution is using multiple injectors [4].

3. The impact of combustion chamber combustion unevenness and instability on the technical condition of a gas turbine

During the operation of the turbine, at fixed rotational speed values of its rotor, the phenomena of combustion chamber outlet flue gas stream non-uniformity and instability appear. The peripheral and radial non-uniformity of the temperature field, and the associated non-uniform flue gas inflow intensity, proves the adverse impact on the heat resistance and high-temperature creep resistance of combustion chamber flame tubes and turbine blades. This phenomenon is caused by uneven load of these elements, leading to their vibration. When these loads are close to the blade specific vibrations frequency, which can lead to their resonance, is a very unfavourable situation. It results in a significant increase of dangerous stresses, deteriorating the strength and durability of the blades. Due to the presence of flue gas temperature field non-uniformity, the designers are forced to decrease the mean temperature downstream of the combustion chamber, which, in turn, adversely affects the turbine characteristics. Another equally disadvantageous phenomenon is the instability of flue gas stream temperature, pressure and velocity, which leads to the pulsation of these parameters. These pulsations, usually low frequency, lead to the presence of additional fatigue stresses in the elements of the combustion chamber and turbine blades [4, 16].

Various types of combustion chamber and gas turbine elements appear within the turbine engine operating process [1, 16]. This is primarily caused by adverse conditions of fuel combustion in the combustion chamber. This leads damage to the flame tubes, a mainly, the turbine blades, in the form of overheating, deformation, creep, burn-through, as well as thermal fatigue of their material (Fig. 5).

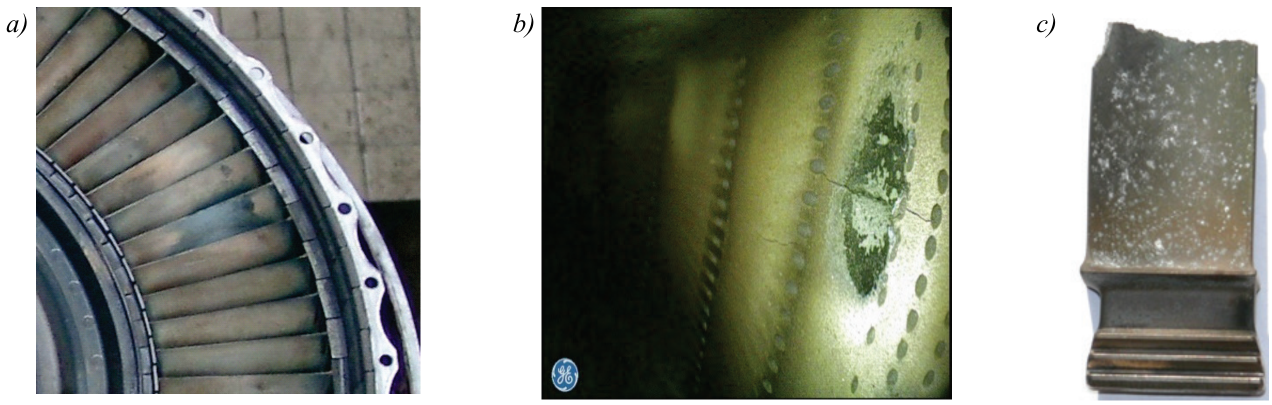

Fig. 5. Forms of gas turbine damage: a) different colours on vanes surfaces exhibiting various overheating degree [13], b) nozzle apparatus vane with an overheating zone, c) rotor blade torn off due to burn-through

Results of metallographic tests covering blades, which were new and blades after various periods of operation, indicated the growth of the heat-resistant coating, numerous thermal and erosive damage. The latter impacts the reduction in its thickness, which impairs blade heat-resistance. Among others, delamination between the heat-resistant coating and the native material of the blade was observed (Fig. 6a). Moreover, transverse and longitudinal cracks were noticed in the layer, as well as propagations of some cracks inside the blade material to a depth of over 500 µm (Fig. 6b). It was also stated, that the oxidation process, and subsequently cracking, is preferential over dendrites or interdendritic spaces. The recorded degradation of coatings also translates to microstructural changes, which undergo within the coating itself, as well as the native material of operated blades (Fig. 6c). The average coating thickness was worn to 30 µm. It was observed that in the case of blades after an extended period of operation, this lead to significant changes of the particle morphology of the strengthening phase γ' and its participation under the coating surface (Fig. 7).

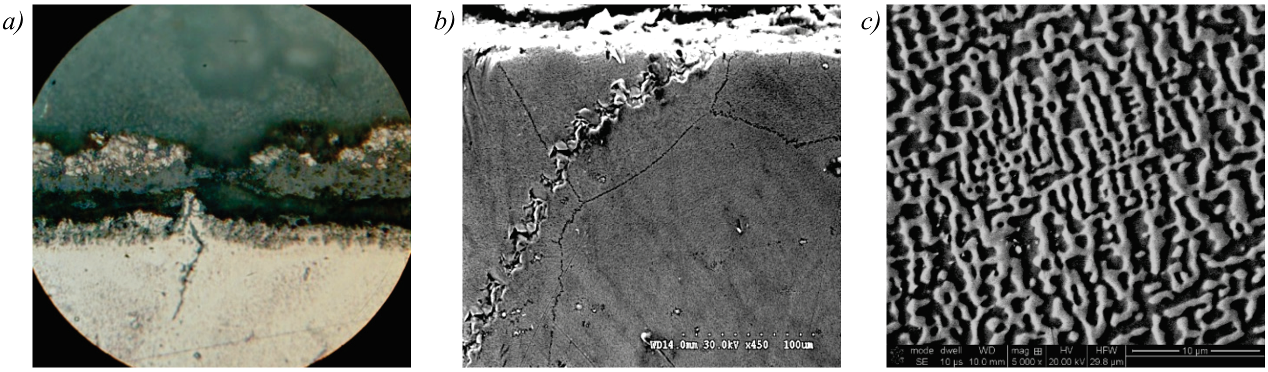

Fig. 6. An example of turbine blade overheating, a) heat-resistant coating delamination and rupture of its material b) SEM microstructure of a rupture with a trans-crystalline character – ×450 c) microstructure of the strengthening phase γ' in lamellar form – ×5000

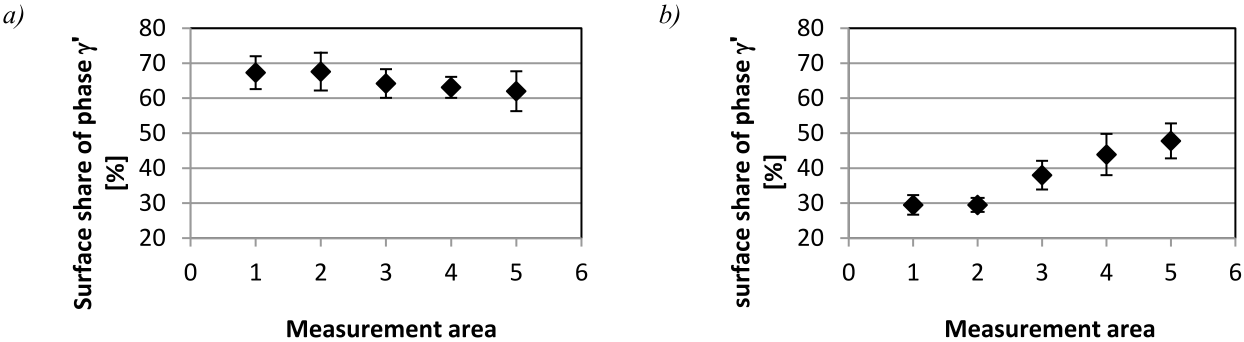

Fig. 7. The surface participation of strengthening phase γ' inside the edge of attack in individual blades: a) new blade, b) a blade after a significant period of operation (l – blade surface)

Observations of structural changes were carried out on transverse (in relation to the blade axis) metallographic micro sections in five areas equidistant from the surface (1). It was stated that the operating conditions result in the growth of the strengthening phase γ' (Fig. 6b). In the case of a new blade, the average size of phase γ' particles is approximately 0.3 µm. As a result of high flue gas temperature impact, this value increases to a level of 2 µm. Moreover, a significant decrease in its participation near the blade surface is observed (Fig. 7b). Such substantial participation of the strengthening phase γ' in the blade alloy structure and its deformation from the cuboid shape to lamellar, has a significant impact on its heat-resistance and high-temperature creep resistance properties [8-12]. Hence, during the operating process, in the presence of excessively high flue gas temperature, the aforementioned damage appears, in the form of overheating, deformations, creeping, burn-through, as well as thermal fatigue of the material.

4. Conclusions

As a result of unevenness and instability of the combustion chamber outlet flue gas temperature field, the gas turbine blade destruction process begins with the destruction of its coating. As a result, the blade material is exposed to direct thermal and chemical impact from the flue gases. Such a situation causes, primarily, material decohesion, which is manifested with adverse changes in the microstructure. The strengthening phase γ' grows and its participation near the blade surface significantly decreases. Decreasing the share of the strengthening phase γ' in the alloy structure is of significant importance to its heat-resistance and high-temperature creep resistance properties. This results in the presence of various types of blade damage, favouring failures of an air turbine engine gas turbine. Ultimately, this can lead to its unreliable operation. An important task of an aviation engine user is the periodic diagnostics of turbine blades with the optical method, which enables a non-invasive evaluation of their technical condition. By using a computer-assisted analysis of blade surface colour changes, it is possible to forecast the failure--free operation period and draw conclusions in terms of their durability.

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