ТРАНСПОРТНЫЕ СИСТЕМЫ
2.9.1 – Транспортные и транспортно-технологические системы страны, ее регионов и городов, организация производства на транспорте;
2.9.4. – Управление процессами перевозок;
2.9.6 – Аэронавигация и эксплуатация авиационной техники;
2.9.8 – Интеллектуальные транспортные системы

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High pressure turbine rotor blades heating duration experimental estimates prior to the bypass turbofan engine start for reducing thermal stresses

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Abstract: Reducing the durability cost of an aircraft product is an issue either addressed at the design stage or causing significant design modifications. Turbine preheating of a gas turbine engine (GTE) allows for the thermal stress of the rotor blades (RB) to be reduced at the engine start without making design changes, but only by implementing the engine heating technology into the operational process. Values of thermal stresses on rotor blades of a high-pressure turbine of a bypass turbofan engine (TFE) with and without heating allow us to determine the change in the total HPT RB damage rate. In the concept of preheating a GTE prior to the start in order to comply with the preheating technology, it is necessary to know the duration within which the RB will heat up to the required temperature. Thus, the research objective, presented in the paper, is to empirically determine the HPT RB heating time, using thermocouples and pyrometers on a full-scale body depending on the methods of air supply for heating and rotor spinning. A distinctive feature of this work is the application of the empirical approach to determine HPT RB heating time to evaluate the feasibility of the GTE preheating technology application prior to the start and the selection of the most efficient heating method according to the duration criterion. Several methods of engine heating prior to the start, using different sets of equipment and the method of supplying hot air to the turbine, were considered. The results of RB heating time measurements made it possible to establish the method of heating with minimal time expenditure prior to the engine start.

Key words: gas turbine engine, high-pressure turbine, rotor blade, preheating, thermal stresses, damage rate.

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Экспериментальные оценки продолжительности прогрева рабочих лопаток турбины высокого давления перед запуском ТРДД для снижения в них термических напряжений

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Аннотация: Уменьшение стоимости жизненного цикла изделия авиационной техники – задача, решаемая на стадии проектирования либо влекущая за собой значительные доработки конструкции. Предварительный подогрев турбины газотурбинного двигателя (ГТД) позволяет уменьшить термонапряженность рабочих лопаток (РЛ) при запуске двигателя без внесения конструктивных изменений, а лишь за счет внедрения технологии подогрева двигателя в эксплуатационный процесс. Значения термических напряжений на РЛ турбины высокого давления (ТВД) турбореактивного двухконтурного двигателя (ТРДД) с применением подогрева и без него позволяют определить изменение суммарной степени повреждаемости РЛ ТВД. В концепции предварительного подогрева ГТД перед запуском для составления технологии подогрева необходимо знать время, за которое РЛ нагреется до необходимой температуры. Таким образом, задача исследования, излагаемого в статье, заключается в эмпирическом определении времени прогрева РЛ ТВД при помощи термопар и пирометров на натурном объекте в зависимости от способов подачи воздуха для подогрева и вращения ротора. Отличительной особенностью проделанной работы является применение эмпирического подхода в определении времени прогрева РЛ ТВД для оценки целесообразности применения самой технологии предварительного подогрева ГТД перед запуском и выбора наиболее эффективного способа прогрева по критерию времени. Рассмотрены несколько способов подогрева двигателя перед запуском с применением различного набора оборудования и способа подачи горячего воздуха на турбину. Результаты измерений времени прогрева РЛ позволили установить способ прогрева с минимальными затратами времени перед запуском двигателя.

Ключевые слова: газотурбинный двигатель, турбина высокого давления, рабочая лопатка, предварительный подогрев, термические напряжения, степень повреждаемости.

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Introduction

The basic details which determine the TFE durability, as a rule, are the HPT RB [1].

The HPT preheating technology prior to the start makes it possible to reduce thermal RB stress due to reducing the temperature deference of a blade airfoil during the start.

Reducing thermal stresses on the RB in non-heated cases and with the use of the proposed technology determines the RB damage rate [2] during the engine start which impacts the frequency of HPT inspections and the reduction of downtime during the maintenance [3].

The heating technology is a supply of hot air, using a ground source (engine heater), to an engine core from the direction of a nozzle [4].

Presuppositions

The investigations to assess the durability of the aircraft engine units have already been conducted by the specialists of the Lul'ka Experimental Design Bureau (G.P. Gogaev, E.Yu. Marchukov, M.A. Bogdanov, I.A. Shubin) [5]. In their proceedings, a modern mechanism of calculating the accumulated damage rate of the major GTE components, considering the effect of flight conditions to increase the engine operation time, has been presented. This methodology assesses the accumulated engine damage rate on the whole, preventing its premature removal.

The investigations to assess the HPT RB durability suppose modelling of the stress-strain state with the further evaluation of acting stresses on a full-scale blade [6]. The Doctor of Technical Sciences I.Kh. Badamshin, in his investigations, was assessing the impact of static and thermal cycle loading on the HPT RB durability by means of the computational methods [7], considering the heating temperature as an input parameter leaving open the question about determining the duration of a hot air supply to attain the required RB temperature prior to the engine start.

The problem to determine theoretically the time of blade heating up to the assigned temperature involves an array of factors [8] to be considered, impacting the heating time, such as a location of air supply, engine heater parameters, ambient temperature, thermal losses related to heat discharge into a disk, etc. Therefore, the issue of the empirical HPT heating time determination prior to the engine start, considering the stated above factors, arises.

In order to form the preheating technology, it is crucial to experimentally obtain temperature heating duration dependencies in conformity with various equipment configurations.

The experimental design techniques and conditions for its conducting

For the purpose of statistical confidence and ensuring the maximum measurement accuracy [9], the experiment was conducted on various days on a completely cooled engine at the ambient temperature of 15 °C. The measurements for each equipment configuration were conducted

Fig. 1. Hot air source is the engine heater

Fig. 2. Pyrometer with a flexible cable and a recording application

five times. The temperatures were assessed in three RB airfoil sections in the radial direction from the root to the peripheral part.

As a source of hot air, a modern engine heater[1] (EH), applied in operation, was used (fig. 1). Its parameters were as follows: supplied air temperature 145 °C, air flow 8000 m^3/h, air outlet diameter 300 mm.

The pyrometer[2] parameters, used to determine the blade airfoil temperature, are as follows: the range of temperature measurement is from −30 up to 600 °C, the spot diameter is from 1.6 mm up to 6.5 mm, the distance range to a measured object is up to 450 mm, the basic error margin is ±1,5%. An application to record the blade temperature, which includes the pyrometer, is shown in Figure 2. A smart phone was used as an application to record.

Conducting an experiment

In the design of CFM56-5B engine, an operational plugged (borescope) port on the engine casing[3] is provided. It is practical to determine the HPT RB temperature (fig. 3) through the port.

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1 AEROSMART SYSTEMS. *An official site “AEROSMART SYSTEMS”*. Available at: https://aerosmart.ru/catalogue/ (accessed: 16.02.2023).

2 TEKKNOW. *An official site JSC “TEKKNOW”*. Available at: https://www.tek-know.ru/catalog/po-vidam-izmereniy/temperatura/pirometry/ (accessed: 20.02.2023).

3 Operation manual of airbus family A320 (2022). 21 p.

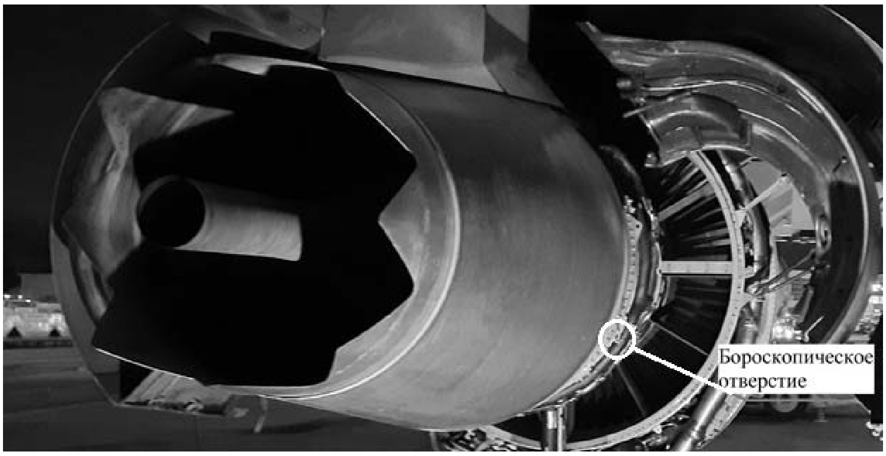


Fig. 3. Operational port on the engine casing used for pyrometry

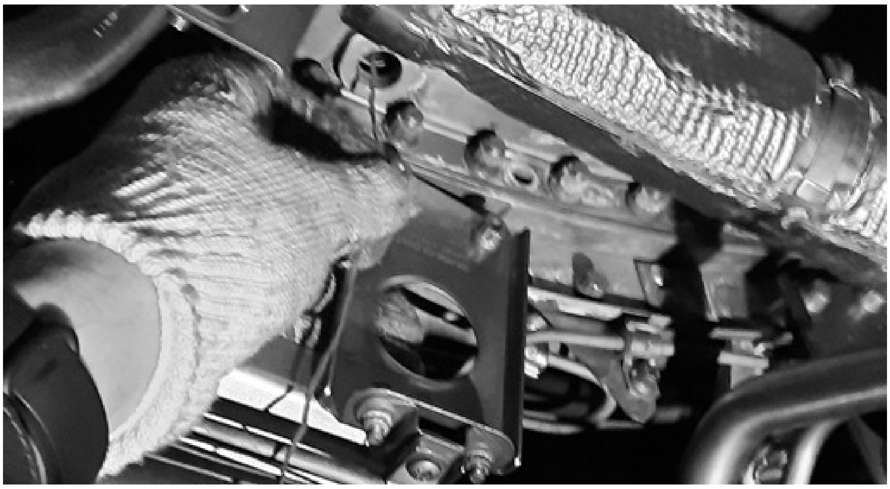


Fig. 4. HPT RB temperature determination through an operational port

Table 1

Dependence of the attained temperature t on heating time τ for three blade sections

Temperature t, °C	15	30	40	50	60	70	80	90	100
Heating time τ_{root}, seconds	0	1:42	2:39	4:46	6:16	8:34	11:18	13:03	15:41
Heating time τ_{mean}, seconds	0	1:29	2:37	4:23	6:11	8:13	10:31	12:48	15:26
Heating time τ_{per}, seconds	0	1:24	2:31	4:17	6:06	8:02	10:25	12:32	15:07

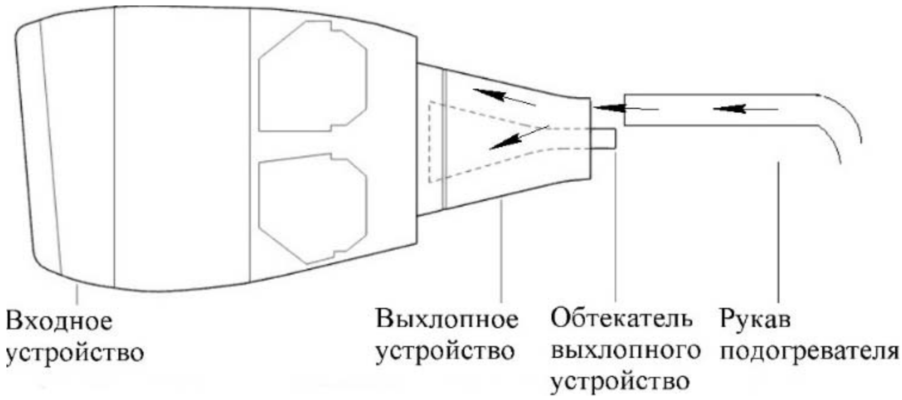
For an access to a leading edge of the HPT RB, a flexible cable in a set of the pyrometer, designed to measure the temperature of metallic surfaces, is used (fig. 4).

Let us consider the possible options of an equipment configuration to preheat the GTE prior to the start.

The equipment configuration 1: an engine heater hose is routed towards the side opposite from a borescope plug (fig. 5, *a*, *b*).

For considering the radial temperature variation, the temperature measurements of the leading edge in three HPT RB sections were carried out: $R_{пер}$ – the peripheral blade airfoil part (R_{per}), $R_{ср}$ – the mean blade airfoil section (R_m), $R_{корн}$ – the root blade airfoil section (R_{root}) (fig. 6).

The arithmetic mean values of heating time τ for configuration 1, based on the results of five measurements, are given in Table 1. Where τ_{root} – heating time measured in the root section of HPT RB R_r, τ_{mean} – heating time measured in the mean section of HPT RB R_m, τ_{per} – heating time measured in the peripheral section of HPT RB R_{per}.



a)

Входное устройство – inlet; Выхлопное устройство – exhaust outlet; Обтекатель выхлопного устройства – exhaust outlet casing; Рукав подогревателя – heater hose

b)

Fig. 5. Equipment configuration 1:
a – heating circuit; *b* – hot air supply

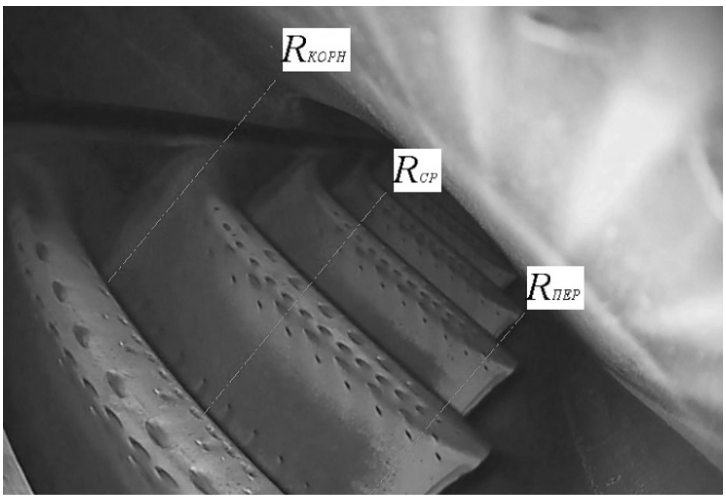
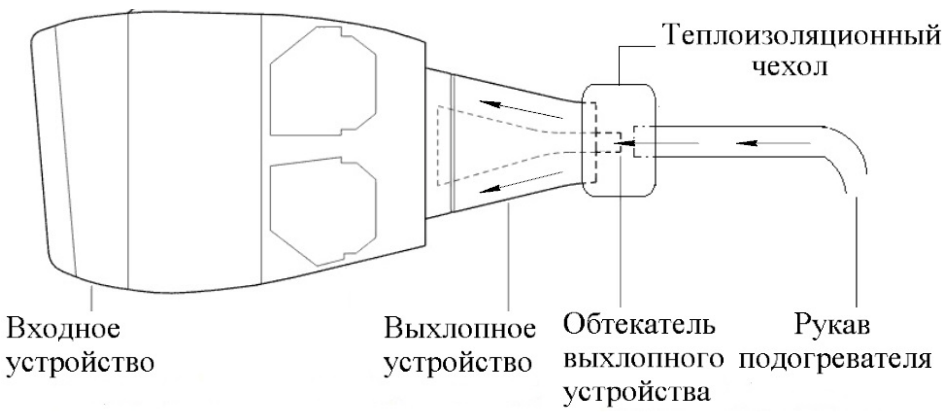
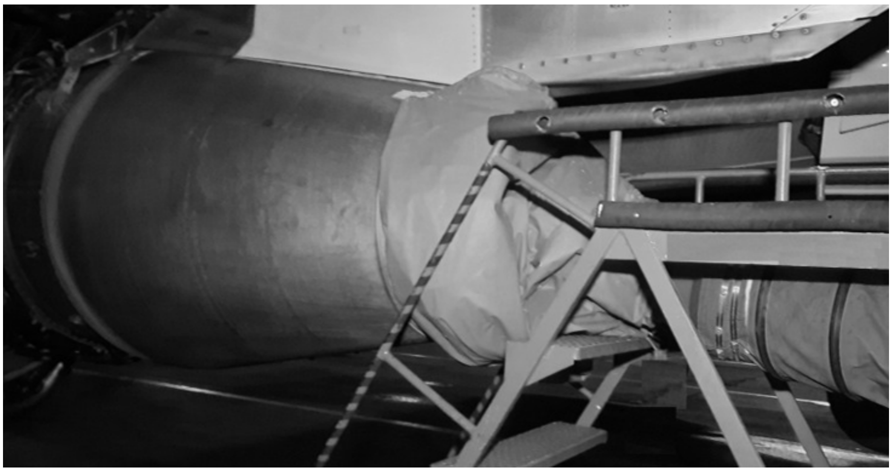


Fig. 6. Temperature measurement points on the HPT RB airfoil



a)

Входное устройство – inlet; Выхлопное устройство – exhaust outlet; Обтекатель выхлопного устройства – exhaust outlet casing; Рукав подогревателя – heater hose; Теплоизоляционный чехол – thermal insulation cover



b)

Fig. 7. Equipment configuration 2 with the application of a thermal insulating cover: *a* – heating circuit; *b* – hot air supply

As the longest heating time τ was observed in the root section of the blade airfoil R_{root} (fig. 6), the further measurements were conducted in the root section of the HPT RB airfoil.

For the partial prevention of thermal losses, the equipment configuration was used, in which, a cover, made from the thermal insulating material, is applied, allowing for air flow leakage through clearances between an air-gas channel of a main duct and a hose of an engine heater to be eliminated. (fig. 7, *a*, *b* – the equipment configuration 2).

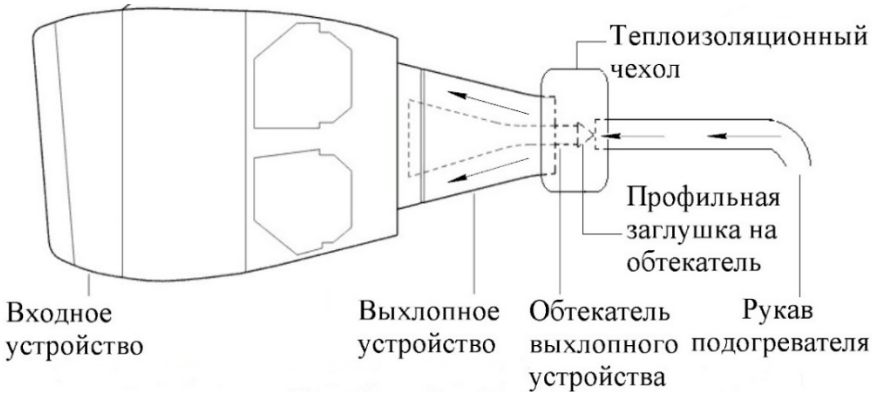
When the cover is used, the low-pressure rotor under the impact of hot airstream from the engine heater is driven into rotation, thus, accelerating the heating process and its uniformity. The arithmetical mean value of heating time τ for the configuration, using the cover according to the results of five measurements, is given in Table 2. Where τ – heating time without rotor spinning, $\tau_{\text{r.sp.}}$ – heating time under rotor spinning.

For more effective flow-around of the exhaust unit center body, a profile plug was used in combination with a thermal insulating cover (equipment configuration 3), which allowed for heating time to be shortened (fig. 8, *a*, *b*).

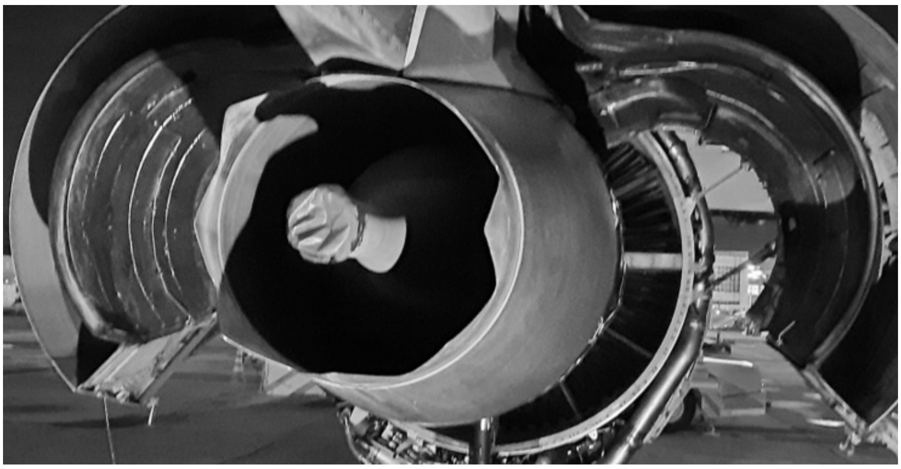
Table 2

Dependence of the attained blade airfoil temperature t on heating time τ
for the configuration with the application of a thermal insulating cover

Temperature t, °C	15	30	40	50	60	70	80	90	100
Heating time τ, seconds	0	1:28	2:33	3:12	5:36	6:18	8:32	9:36	11:30
Heating time $\tau_{r.sp.}$, seconds	0	1:07	1:49	2:45	4:01	4:44	6:43	7:41	8:53



a)
Входное устройство – inlet; Выхлопное устройство – exhaust outlet; Обтекатель выхлопного устройства – exhaust outlet casing; Рукав подогревателя – heater hose; Теплоизоляционный чехол – thermal insulation cover; Профильная заглушка на обтекатель – profile plug



b)
Fig. 8. Equipment configuration 3 with the application of a thermal insulating cover and a profile plug: a – heating circuit; b – application of a profile plug

The arithmetical mean value of heating time τ for equipment configuration 3, based on the results of five measurements, are given in Table 3.

Summary dependencies of the attained blade airfoil temperature t on heating time τ for the various configurations are given in Figure 9.

Table 3

Dependence of the attained blade airfoil temperature t on heating time τ for the configuration with the application of a thermal insulating cover and a profile plug

Temperature t, °C	15	30	40	50	60	70	80	90	100
Heating time τ, seconds	0	1:17	2:02	3:06	4:48	5:45	7:01	8:34	9:22
Heating time $\tau_{r.sp.}$, seconds	0	0:58	1:42	2:14	3:42	4:13	5:41	6:19	7:16

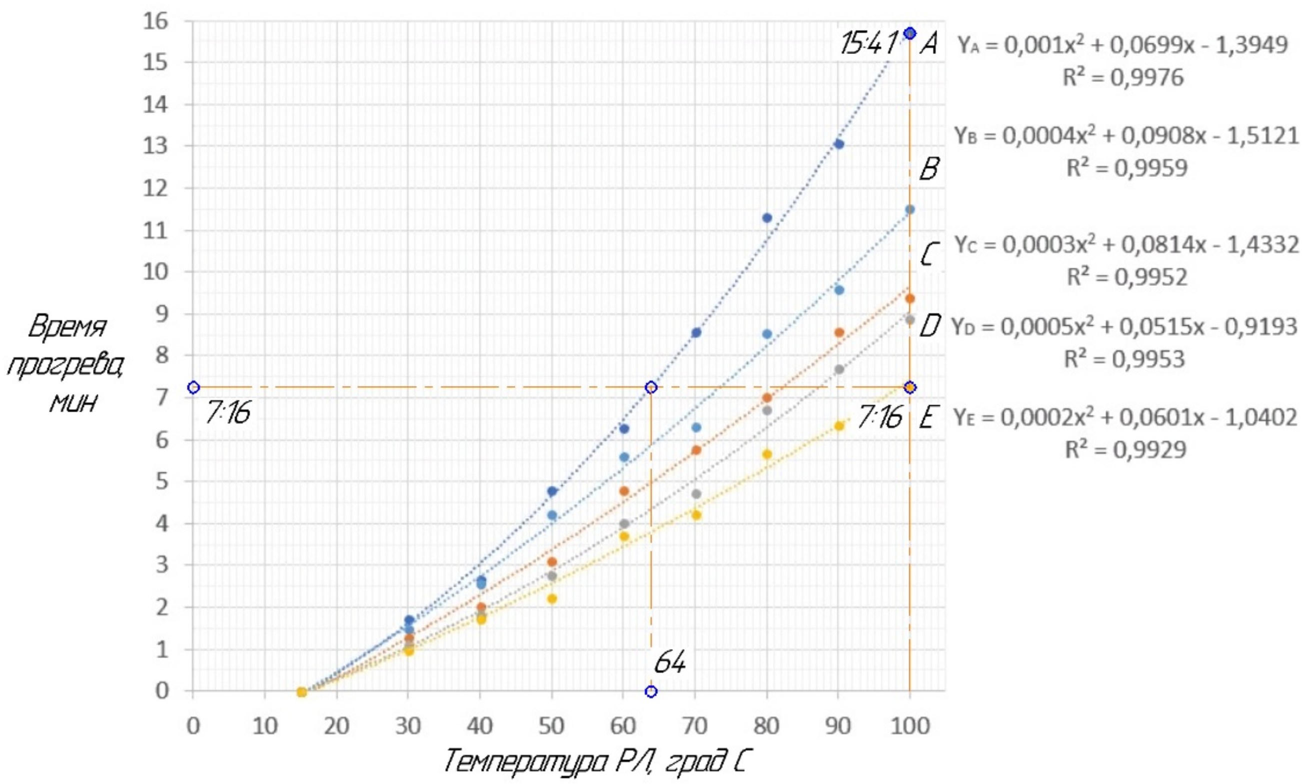


Fig. 9. HPT RB heating time for the various equipment configuration:

graph A – the equipment configuration with an engine heater hose routed to the side opposite a borescope plug (configuration 1);
graph B – the equipment configuration with the application of a thermal insulating cover (configuration 2);
graph C – the equipment configuration with the application of a profile plug and a thermal insulating cover (configuration 3);
graph D – the equipment configuration with the application of a thermal insulating cover and rotor spinning (configuration 2 with rotor spinning);
graph E – the equipment configuration with the application of a profile plug, a thermal insulating cover and rotor spinning (configuration 3)

Conclusion

Within the framework of the method development to increase the TFE turbine unit durability by reducing temperature stresses in the HPT RB airfoil during the engine start by means of RB preheating, the experimental estimates of blade heating time up to the temperature of 100 °C were carried out.

The minimum blade heating time up to the temperature of 100 °C is attained using the equipment configuration with the application of a profile plug, a thermal insulating cover, rotor spinning and amounts to 7 minutes 16 seconds.

Within the stated time, while using the equipment configuration under which an engine heater hose is routed to the side opposite from a borescope plug, the blade airfoil temperature of approximately 64 °C is attained.

The stated result is twice as much as the event of the equipment configuration under which an engine heater hose is routed to the side opposite from a borescope plug and can be used while developing a task card of HPT heating.

As a result of experimental data processing, significant, by a correlation criterion [10], regressional dependences [11] of blade heating time on the required heating temperature were also obtained. These dependencies will be used in a mathematical model to estimate a blade durability [12] variation.

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