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Gas dynamic improvement of the axial compressor design for reduction of the flow non-uniformity level

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Abstract. Circumferential nonuniformity of gas flow is one of the main problems in the gas turbine engine. Usually, the flow circumferential nonuniformity appears near the annular frame located in the flow passage of the engine. The presence of circumferential nonuniformity leads to the increased dynamic stresses in the blade rows and the blade damage. The goal of this research was to find the ways of the flow non-uniformity reduction, which would not require a fundamental changing of the engine design. A new method for reducing the circumferential nonuniformity of the gas flow was proposed that allows the prediction of the pressure peak values of the rotor blades without computationally expensive CFD calculations.

1. Introduction

Circumferential nonuniformity of the gas flow is one of the main sources of vibration excitation of turbomachinery rotor blades [1-4]. Due to the circumferential nonuniformity of the gas flow, the RW blades are under higher dynamic stresses. All this leads to the destruction of the blades.

Several approaches are implemented in practice to reduce the high dynamic stresses. The first method is detuning from dangerous harmonics by changing the natural frequency of the blade [5]. The second way to improve the dynamic strength of the rotor blades is to increase the blade endurance limit through the optimization of mechanical-thermal treatment and using the methods of surface hardening of the blade [5]. The third method involves the direct reduction of gas-dynamic flow nonuniformity. There are several variants in this case: an increase of the axial clearance between the RW and GV, changing the stagger angles and the pitch of GV blades into non-uniform ones around the circumference [6,7,8], changing the number of struts or using the inclined struts. The main drawback of the third method is an inability to apply this approach to existing engines.

The goal of this research was to find the ways of the flow non-uniformity reduction, which would lead to a decrease in the level of dynamic stresses in RW blades located in front of the annular frame, but would not require a fundamental engine design changing at the same time.

2. Problem statement

A five-stage intermediate pressure compressor was selected as the test object (Figure 1). This compressor was designed and manufactured at Samara engine building company JSC "Kuznetsov" [9]. The problem of the destruction of rotor blades of the fifth stage exists for the compressor because of the influence of the downstream annular frame of the gas turbine engine. Seven struts of different cross-sections are unevenly distributed in the flow passage of the annular frame casing. Annular frame struts are the cause of gas flow nonuniformity, which extends its negative impact of upstream. High pressure zones occur, and the capacity of channels located opposite the struts decreases (Figure 2-3).

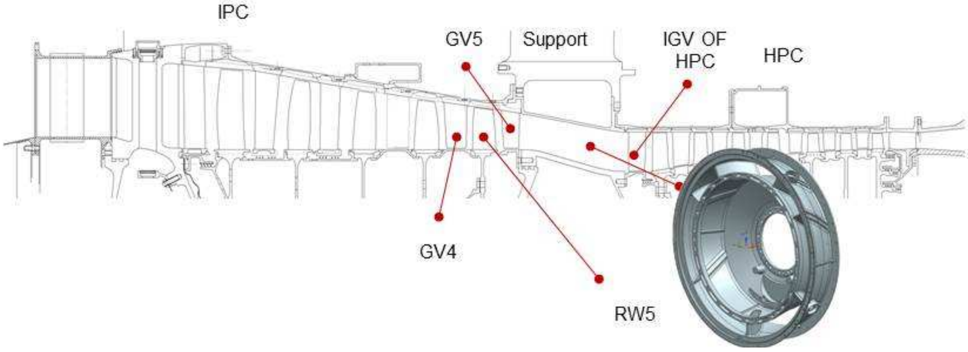

Figure 1. The diagram of the compressor under investigation.

3. The proposed method

There are experimental studies that prove that the aerofoil cascade, which is located in front of the cylinder, streamlined by the flow, enhances the upstream transmission of the high pressure zone [10]. The proposed method for reducing the circumferential nonuniformity of the gas flow is based on the results of the study [10]. It consists in distancing the leading edge of annular frame struts (in this case - the cylinder) from the trailing edge of GV blades located upstream (in this case - the cascade) in order to neutralize the negative effects. At the same time, an important requirement is the necessity to maintain the internal cavities of the annular frame struts for placement of the engine system.

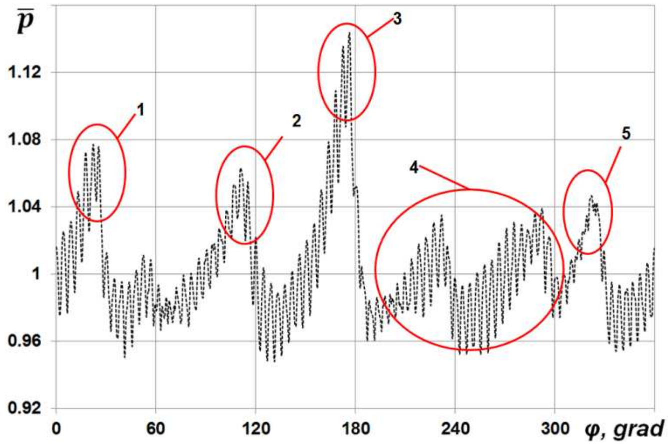

Figure 2. Circumferential distribution of relative static pressure after the RW.

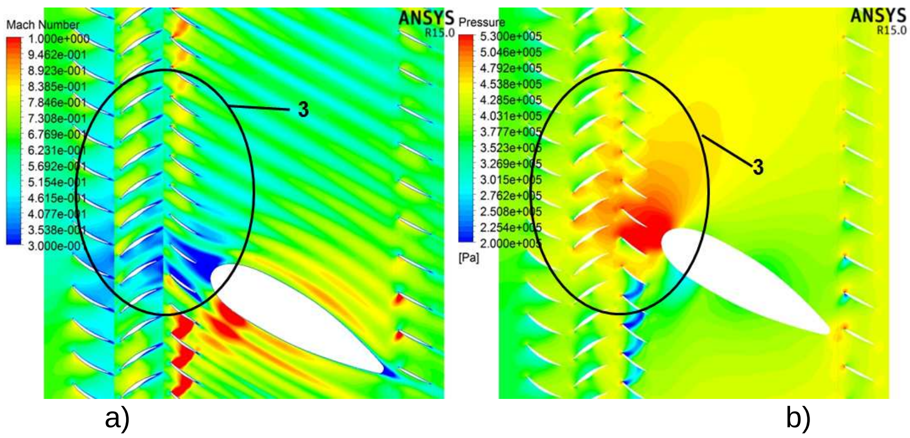

Figure 3. Mach numbers (a) and static pressure (b) fields near the annular frame strut.

4. Development of the parametric model of annular frame struts

Struts can be divided into three groups according to the maximum thickness of profile C_m: thick (strut No. 1), medium (struts No. 2,4,5) and thin (struts No. 3,6,7).

To implement the chosen method of the nonuniformity reduction, the parametric models were developed for each type of the strut. The models make it possible to adjust the position of the leading edge, pressing the profile of the strut, but maintaining the thickness and the rest of the profile by specifying the desired value of shifting (Δb) (Figure 4). Parametric models take into account the limitations related to the location of the engine systems in the struts.

5. Analysis of elementary pressure peaks after the RW

To analyse the effect of leading edge shifting along the circumferential nonuniformity of the gas flow, the set of computational models of the compressor was created using the parametric models of struts. All of them were full circle models and consisted of five domains: GV of the fourth stage, RW and GV of the fifth stage, the middle annular frame, and IGV of HPC. The annular frame contained only two struts disposed facing each other with the same thickness in each model. Such models were called elementary, and were created to assess the contribution of each type of strut in the total circumferential flow non-uniformity.

Moreover, leading edge shifting of struts with $\overline{\Delta b} = 0$, $\overline{\Delta b} = 0.2$, $\overline{\Delta b} = 0.4$, $\overline{\Delta b} = 0.6$, were set for each type of struts in different models. Thus, the total number of computational models was 12.

Construction of the finite volume mesh (Figure 5) was carried out with the help of the *AutoGrid* module of software package *Numeca*. Initially, all blade rows contained only one blade passage except for the annular frame. At subsequent stages, the created mesh was passed to the Ansys CFX software package for creating a full circle model and setting the computational model. The estimated number of finite volumes in the mesh was equal to *45 million* in each elementary model.

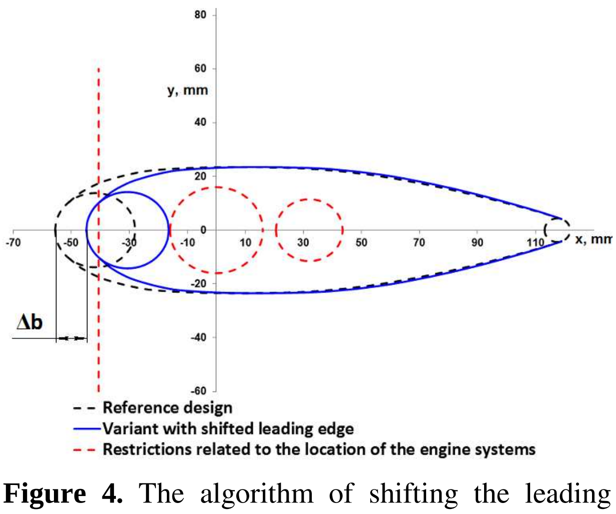

Figure 4. The algorithm of shifting the leading edges of struts in case of a thick strut.

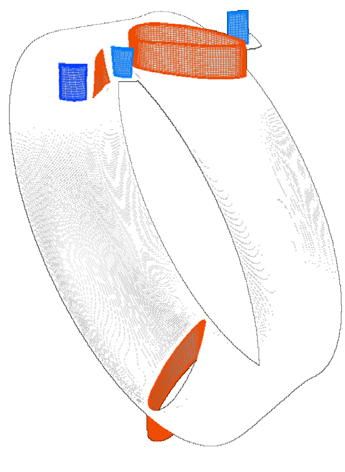

Figure 5. The finite volume mesh for the elementary model with thick struts.

The calculation and analysis of the results were also carried out in Ansys CFX using the supercomputer of SSAU "Sergei Korolev". The values of total pressure p_t and total temperature T_t were set as inlet boundary conditions. The direction of the flow at the computational domain inlet was defined using direction cosines. Static pressure p was defined as an outlet boundary condition. The ideal gas with the properties of dry air was used as the working fluid.

The total pressure and the temperature, and the flow direction at the inlet resulting from previous calculations [11] and the static pressure at the outlet of the computational model were set as the boundary conditions.

Parameters of finite volumes meshes and settings for computational models were chosen according to the recommendations given in [12-13]. Computational models were verified in [6, 11] while assessing the level of vibrations in rotor blades. This indicates the reliability of calculations performed within the research described in this paper.

As the result of investigation, the circumferential distributions of the relative static pressure in the section behind the RW for each type of the strut with all values of leading edge shifting were obtained. It should be noted that obtaining the pressure distribution only for one model took a long time, both in terms of creation of the model, and the calculation process. These distributions were averaged to obtain the so-called elementary peaks (Figure 6). The level of the mean pressure after the RW (red line) was correlated with zero of the y-axis for a visual representation of the elementary peaks. Figure 7 shows a field of static pressure distribution for the case of the thick strut with $\overline{\Delta b} = 0$.

It is obvious from the graphs form, in Figure 6, that annular frame struts lead to the appearance of complex forms of pressure peaks after the RW. The peaks have not only maximum jump h (the positive upper part of the graph), but also go to the negative part of the graph into decline h_1. A similar pattern is seen in Figure 7 when following in the positive direction of angle φ.

The complex peak shape can be caused by the rotation of the RW blades in the area of the circumferential nonuniformity of the gas flow.

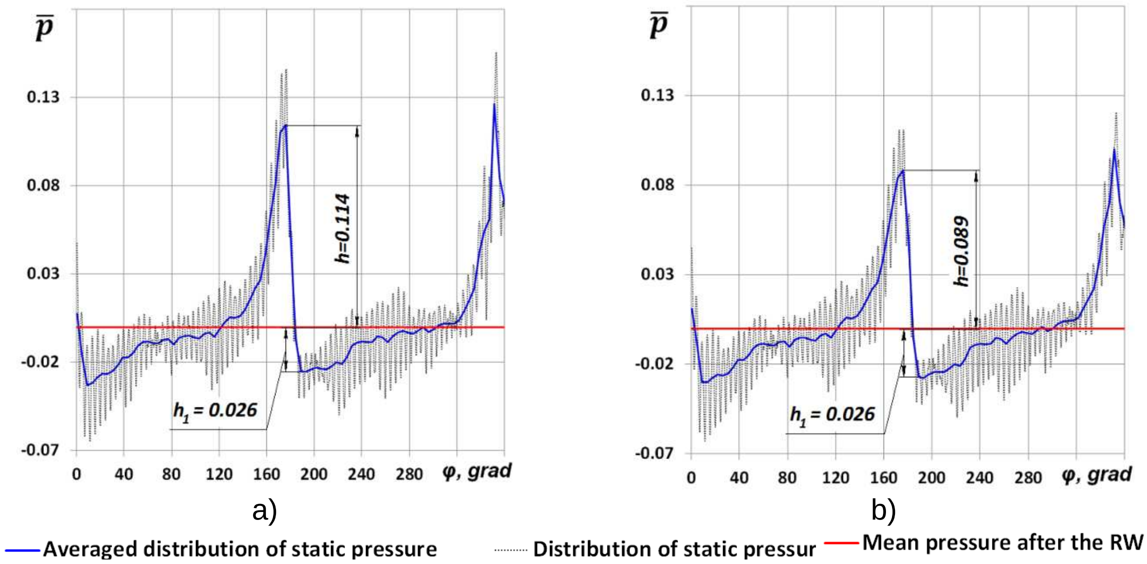

Figure 6. The distribution of the relative static pressure in case of the thick strut with the leading edge shift of $\overline{\Delta b} = 0$ (a), $\overline{\Delta b} = 0.6$ (b).

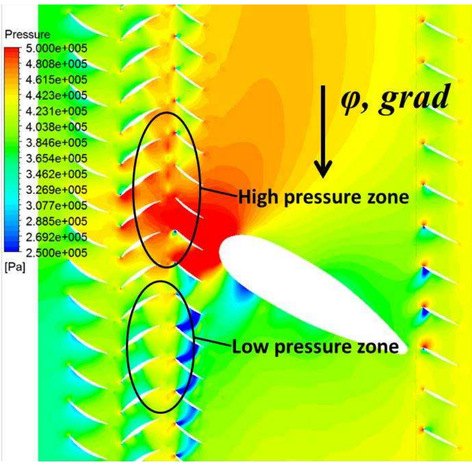

Figure 7. The field of static pressure for the elementary model with a thick strut with the shifted leading edge of $\overline{\Delta b} = 0$.

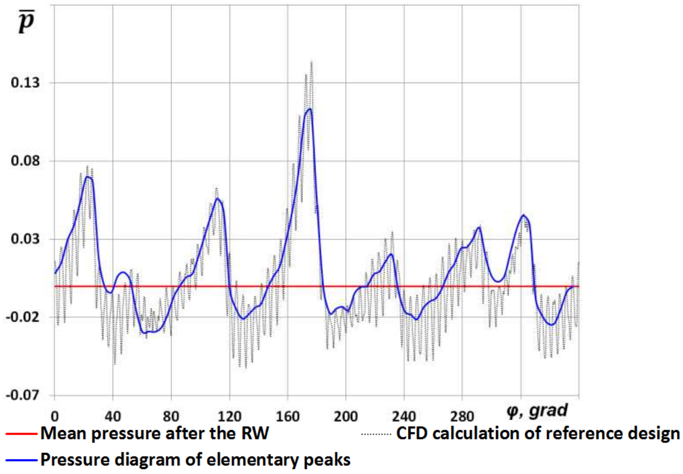

Figure 8. Comparison of the relative static pressure graph after RW for the reference design of the 7-strut annular frame and the graphic obtained by elementary models.

The maximal jump of pressure peaks *h* decreases (the upper part of the graph), while the value of the leading edge shifting is increasing. It is worth noting that the maximum failure of pressure peaks h_1 (the bottom part of the graph) does not depend on the shift of the leading edge and it is constant in all charts. Similar results were obtained for other types of struts.

To verify the adequacy of the obtained dependences, the graph from the individual elementary peaks of each type of the strut was assembled and compared with the graph for the reference design of the seven-strut annular frame (Figure 8).

Also, the distribution of the relative static pressure after the RW of the similar compressor, but with the experimental 13-strut annular frame, was obtained in previous studies [14]. Thick and medium struts in this annular frame correspond to the same struts in the seven-strut annular frame, and thin struts have the twice smaller thickness than the thin strut in seven-strut annular frame.

A similar investigation aimed at the identification of elementary peaks was conducted for that annular frame. Comparison of the chart from the elementary peaks with the chart received in the calculation of the reference design of the 13-strut annular frame is shown in Figure 9. In general, graphics derived from the elementary peak, describe the pressure distribution after the RW well.

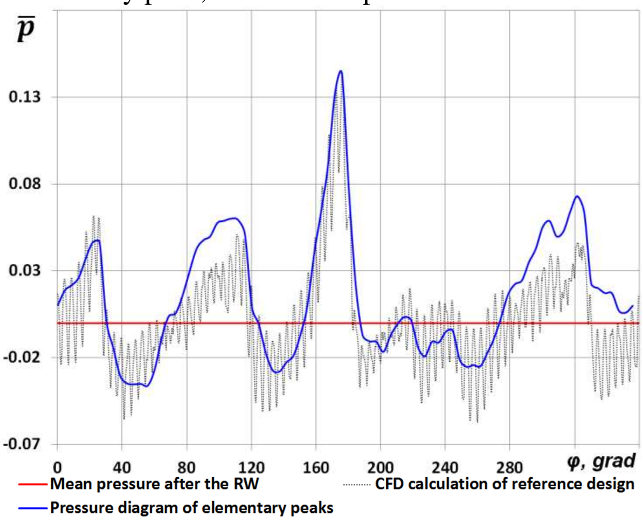

Figure 9. Comparison of the graph of relative static pressure after RW for the reference design of the 13-strut annular frame and the graphic obtained by elementary models.

6. Searching for the equations of the peak height dependence on the leading edge shifting

In order to use the obtained results, it is necessary to describe the dependence of pressure peaks on the shift of the strut leading edge via equations. That was the next step of the study.

Quadratic equations were derived for each type of the strut using the regression analysis techniques, describing the effect of the shift of leading edge (Δb) on pressure peak height (h). Equation 1 corresponds to the thick strut, Equation 2 to the medium strut and Equation 3 to the thin one.

$$h = 0.001\Delta b^2 - 0.135\,\Delta b + 7.5 \quad (1)$$

$$h = 0.001\Delta b^2 - 0.095\,\Delta b + 4 \quad (2)$$

$$h = 2.64\cdot 10^{-18}\Delta b^2 - 0.02\,\Delta b + 2 \quad (3)$$

Pressure peaks in the strut vicinity were constructed using the found equations. These charts were compared with the averaged peaks obtained at the previous stage (Figure 10). The graphs obtained by the equations for all types of struts and all the values of the leading edge shift are in good agreement with averaged pressure values from CFD calculation.

Thus, the so-called surrogate model was created, by means of which the value of the pressure peak behind the RW can be predicted at the preliminary stage of investigation under certain provisions of the leading edges of the annular frame struts.

Using the received regression equations, such configuration of the annular frame was found, which will reduce the pressure peaks values after the rotor wheel of the fifth stage of the IPC.

Application of leading edge shift of annular frame struts allows for not only quantitative changes in the values of the pressure peak behind the impeller (Figure 11). The proposed method also provides a better quality structure of the flow in the compressor: field becomes more uniform, the high-pressure zone reduces its impact on the blade rows and on the located upstream.

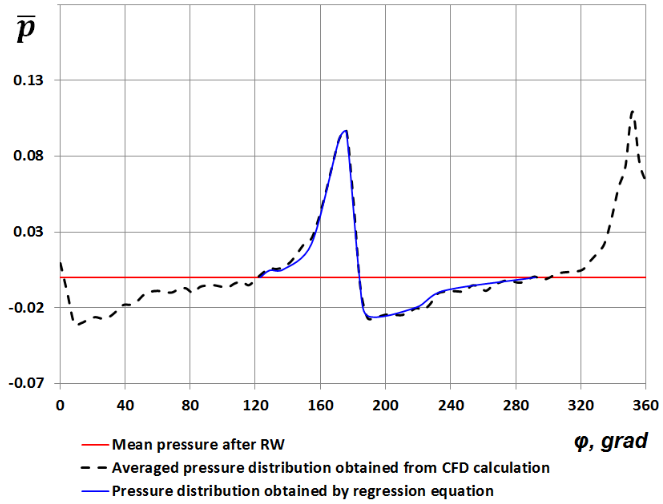

Figure 10. Comparison of the peak shape obtained by regression equation (1) and from CFD calculation for the thick strut with the leading edge shift of $\overline{\Delta b} = 0.4$.

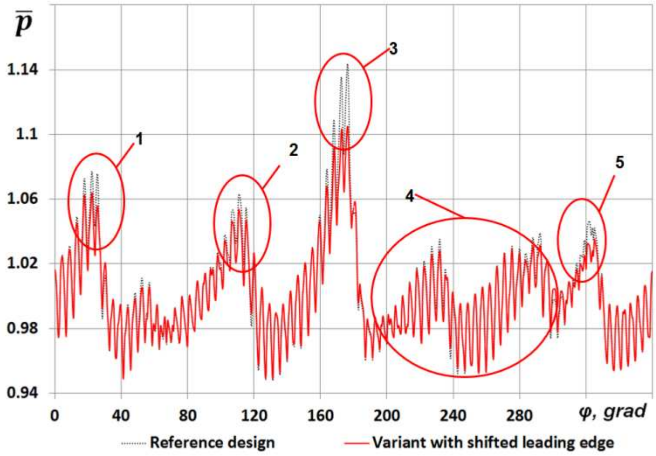

Figure 11. Circumferential distribution of the relative static pressure behind the RW for the reference design of the seven-strut annular frames and the annular frame with shifted leading edges.

7. Conclusion

As studies have shown, the circumferential unevenness of the gas flow in the compressor of the gas turbine engines can be reduced by a minimum interference in the design. It is enough to alienate its source (the annular frame strut) from the elements, experiencing the negative impact of circumferential unevenness of the gas flow (rotor blades located upstream). This is accomplished by shifting the leading edges of the annular frame struts.

The value of the leading edges shifting depends on the established restrictions, requiring the retention of the internal cavities of the annular frame struts to accommodate various engine systems. According to these restrictions and with the help of created equations, the decrease of pressure peaks behind the RW, leading to the appearance of high dynamic stresses in the blades can be achieved.

The advantage of presented method is that it makes possible to predict the pressure peak level behind the RW of the particular design of the annular frame struts without the long process of preparation of the computation model, calculation and post-processing of the results. This can accelerate the design process of new compressors and design refinement of existing units.

8. Acknowledgments

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References

[1] Ivanov V 1983 *Kolebaniya rabochego kolesa turbomashin (Vibrations of turbomachinery impeller)* (Moscow: Mashinostroenie) p 224
[2] Vorob'ev Yu 1988 *Kolebaniya lopatochnogo apparata turbomashin (Vibrations turbomachinery blading)* (Kiev, Nauk. Dumka) p 224
[3] Cohen H, Rogers G and Saravanamuttoo H 1996 *Gas Turbine Theory, 4-th edition* (Longman Group Limited) p 455
[4] Logan E. 2003 *Handbook of Turbomachinery* (CRC Press) p 880
[5] Birger I, Shorr B and Iosilevich G 1993 *Raschet na prochnost' detalei mashin (Strength analysis machinery parts)* (Moscow: Mashinostroenie) p 640
[6] Kolmakova D, Popov G, Shklovets A and Ermakov A 2014 *Proc. of the ASME 2014 Gas Turbine India Conference GTINDIA2014,* Paper No. GTINDIA2014-8203
[7] Sladojević I, Sayma A and Imregun M 2007 *Proc. of the ASME Turbo Expo* **5** 683–700

[8] Yang Y, Yang A, Dong R, Chen E and Dai R 2012 *Hangkong Xuebao/Acta Aeronautica et Astronautica Sinica* **33(4)** 588-96
[9] JSC "Kuznetsov", Accessed July 20, 2015. http://www.kuznetsov-motors.ru/en
[10] Saren V 1984 *Flow around irregular lattice of plates placed in front of the cylinder Technical Report* (Moscow: Central Institute of Aviation Motors) p 36
[11] Ermakov A, Shklovets A, Popov G and Kolmakova D 2014 *Research J. of Applied Sciences*, **9(10)** 684-90
[12] Matveev V, Popov G, Goryachkin E and Smirnova Y 2014 *Research J. of Applied Sciences* **9(11)** 784-8
[13] Popov G, Goryachkin E, Baturin O and Kolmakova D 2014 *Int. J. of Engineering and Technology* **6(5)** 2236-43
[14] Popov G, Kolmakova D, Shklovets A and Ermakov A 2015 *IOP Conf.Series: Materials Science and Engineering* **90(1)** 01205