IMPROVEMENT OF THE DESIGN AND METHODS OF DESIGNING TUBULER AIR-TO-AIR HEAT EXHANGERS COOLING SYSTEMS OF GAS TURBINES

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Abstract

Analyzes the cooling system of high-temperature turbine gas generator GTE: shows the new design of tubular air-to-air heat exchangers with an effective convective cooling and optimized system regulation.

1 Introduction

The construction or the modifications of high temperature turbines in the modern and future jet engines is a complex task. The task revolves around increasing the effectiveness of cooling methods used for the turbine blades which are the critical parts in any gas turbine engine, as this determines the life and reliability and the life of a gas turbine engine as a whole. Reducing the temperature levels of the turbine blades greatly depends on the amount of cooling air that can be effectively used for this purpose. Modern turbine nozzle vanes require approximately 8-10% of the cooling air taken from the compressor, in order to ensure their functionality. However, turbine rotor blades cannot, for structural reasons, pass such a large quantity of cooling air in the internal cavity. Structural dimensions of the lower end of the lock turbine impeller blades, its side surfaces and its platform extension, all of these together limits the maximum amount of the cooling air, which can be brought into their internal cavity. Its range is about 3-5 % of the total air passing through the high pressure compressor of a GTE.

A significant increase in the amount of cooling air that passes through the high pressure compressor is also unacceptable because it results in a reduction in the efficiency of the GTE. Along with these problems, there are other reasons for limiting the amount of air in the cooling system of the turbines in a GTE. The increase of the compression ratio of the compressor results in an increase in temperature of air exiting the compressor. Secondly, the next generation of engines demands an increase in the temperature of the gas entering the turbine. Therefore, as the demand for cooling the turbine parts increases, and the possibility of cold air being present in the engine reduces due to decrease in its cooling capacity. Under these circumstances it is advisable to use heat exchanger to reduce the temperature of the air used in the cooling system, which aids in the design and development of new and more efficiently cooled turbine blades.

2 Heat exchanger with cylindrical tubes having a cross flow cooling air, Installed in the Second contour of the Turbofan engine

Experience from previous designs of heat exchangers installed in the cooling system of the high pressure turbine shows that it is most appropriate to use small diameter cooling tubes. The heat exchanger used to cool the high-pressure turbines [1] of AL-31F turbofan with afterburners has been taken as the basic design, as it can be considered as a suitable model which has the possibilities of improving its efficiency. In the engine casing [Figure 1] 64 modules of heat exchanger with multiple line bundles Ǿ5x0.3 mm are installed in the outer contour of the engine, and a cross flow with the overall propulsive movement of the cooling air of the second circuit [Figure 2]. In the heat exchanger, the air is fed from the cavity above the flame tube of the combustion chamber, into two rows of tubes which are made from material chromium steel. Each row has three tubes which has a spacing of 1.5 mm [Figure 3] and in total there are 384 tubes (section B-B of Figure 1).

The relative flow of cooling air which enters the heat exchanger is 9.5% G_k. The temperature of the cooling air is reduced up to 150 deg Celsius and the pressure loss in the tubular duct is 13%. These parameters correspond to a heat exchanger with an efficiency of ε = 0.45.Advanced air to air heat exchangers (air heat exchanger) are should have a performance indicator ε = 0.75–0.85, at a total pressure loss of gas in tubular heat exchanger channels between 4 and 8%, and no more than 1.0 - 1.5% of the bypass air. For this purpose we have developed the following variants of heat exchangers: Cylindrical tubes of diameter 6 mm and thickness 0.3 mm and an elliptical tube of equivalent perimeter (7.3 * 4 mm). Both the cases have been analyzed for different tube lengths of 110 mm and 800 mm

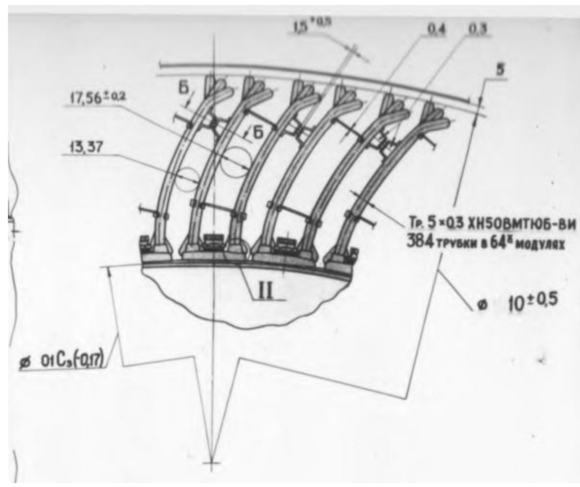

Fig. 1.Configuration of the tubes of a heat exchanger along the radial direction

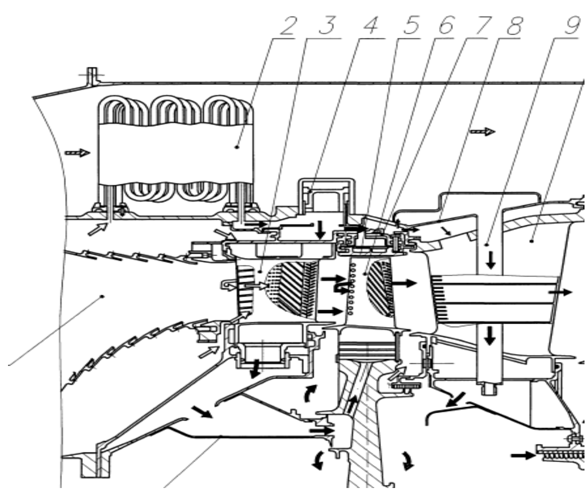

Fig. 2 Construction of the turbine with heat exchanger

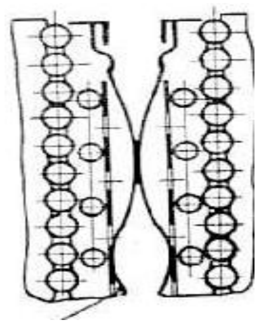

Fig. 3 Arrangement of pipes in the heat exchanger

The scheme of installation of tubes are as follows - row formation, chess formation or a combination of both with different tube placements, which provides drag reduction and improves the efficiency of the cooling gas in the heat exchanger. The schematic of the turbine cooling system shown in Figure. 2 shows that all of the cooled air that passes through the air-air heat exchanger is used to cool the nozzle and the turbine wheel. In order to accomplish this, the cooling air is passed through the interior of the deflector which is mounted the rear cavity of the nozzle and then through a canal in which a deflector is installed to send the air to cool the turbine rotor blades.

2. Construction of a turbine which cannot accommodate a Heat exchanger

Not all construction designs of turbines for turbofan engines can accommodate the heat exchanger at the entrance of their cooling systems. for example, in many designs, the air for cooling the turbine nozzle vanes of a High Pressure Turbine (HPT), which largely determines the life and reliability of the entire engine, is taken from the cavity above the flame tube, where it is impossible to place a Heat exchanger[Figure 4].

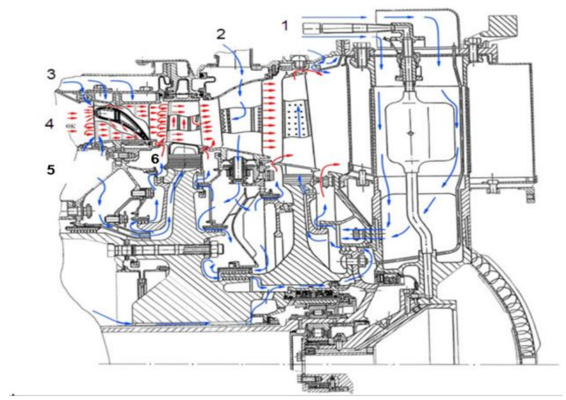

Fig. 4. Construction of a turbine without heat exchanger and its cooling mechanism.

1- Inlet for the cold air from the exit of the high pressure compressor(HPC); 2- inlet for the cold air from the intermediate stage of the HPC; 3- inlet of the cold air from the cavity below the flame tubes of the combustion chamber; 4- Inlet for the cold air into the High pressure turbine(HPT); 5- inlet of the cold air from the cavity below the combustion chamber into the rotor blades of the HPT; 6- air flowing in the gap between the nozzle and the rotor blades of HPT.

3. Improving the design and effectiveness of the Heat exchanger

Many of the modern turbofan engines for civilian and military uses have had their maximum turbine inlet temperature increase significantly reaching approximately 1850-1950°C. The cooling capabilities have also decreased because of the high pressure rise in the compressor, which has reached 40-50 times the inlet pressure, and for highly advanced turbofan engines it has reached 60 times the compressor inlet pressure. Increasing the quantity of cooling air inside the turbine is illogical because it adversely affects the performance of the engine. Therefore, along with the improvement of the blade cooling system and its thermal barrier coatings, it is necessary to improve the air pre-cooling system at the entrance to the nozzle unit or the impeller of the turbine in a turbofan engine, by installing a more efficient heat exchanger which reduces the temperature of the coolant air than those used in earlier models.

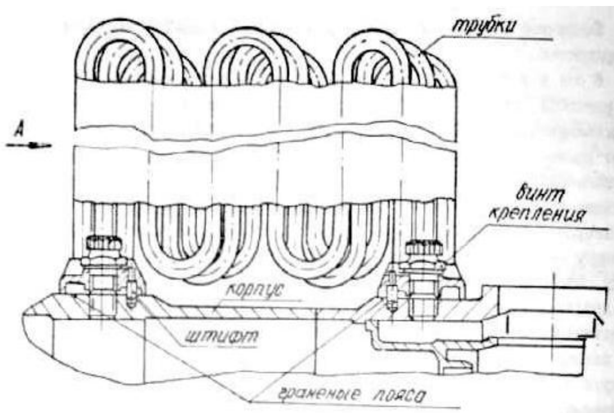

Fig. 5. Structural layout of a tubular air-air heat exchanger with cross flow, located in the second contour of Turbofan engine.

Calculations were done based on the known experimental data. The criterion that characterizes the so called active surface heat transfer has been addressed. From the experimental data that was obtained we have determined the point of separation of turbulent air flow on the surface of the oval channels with the airflow in the longitudinal direction.

3.1. Calculations for air-air cross flow heat exchanger with cylindrical tubes, whose construction is shown in Figure. 5

Experimental results of the heat exchanger shown in Figure. 5. have shown a temperature drop of up to 120˚C. For future reduction of the temperature of the gas, we can increase the surface area of the heat exchanger and can also add intensifiers on the inner surface of the smooth tubes as shown in [3]. In order to achieve this we can use circular diaphragms in the inner surface of the tubes to induce turbulence in the boundary layer. To this end we can also consider changing the configuration of the heat exchanger by changing to elliptical pipes rather than cylindrical pipes, thereby increasing the effective surface area for heat transfer.

The purpose of this calculation is to determine the required heat transfer surface area on the outer surface of the pipe and total length of tubes for a given value of temperature drop of the hot air, which is taken as 232°K, i.e. an increase of almost two fold. The air flowing inside the tubular heat exchanger comes from the outlet of the compressor at a temperature of 809˚K. The outer diameter of the tubes has been increased by 20% and taken as 6mm while the thickness has been maintained the same i.e. 0.3 mm. The methodology for calculations has been shown in [3]. There are 64 such heat exchanger blocks in the engine. the mass flow rate through one block is 0.062 kg/sec. All of these blocks are arranged along the circumference of the combustion chamber as shown in figure 5.

The data for the calculations are as follows: mass flow rate of hot gas through one tube is 0.0104 kg/sec, acceptable pressure loss inside the heat exchanger Δp_{hot}=1.97*10^5 Pa, Pressure of the hot air at the inlet of the heat exchanger is 23.2*10^5 Pa. For the cold air, the data is as follows; Velocity of the gas at the entrance of the heat exchanger bloc is 45 m/s; pressure is $3.6*10^5$ Pa; temperature of the cold air is 450°K.

Heat transfer calculations performed on the Heat exchanger has shown that the heat transfer coefficient value of the walls of the heat exchanger as 501 w/m^2, the average logarithmic temperature difference to be 185°K, the desired outer surface area as 0.166 m^2 and the overall length of the pipes in one bloc of heat exchanger to be 8.81 m. The overall length of the pipes of the heat exchanger shown in figure 5 is 3.6 m.

However, the diameter of the tubes of that heat exchanger is lesser by 20%. So, the process of increasing the efficiency of the heat exchanger demands an almost double the original length while increasing the outer diameter of the pipes.

From a construction point of view it is possible to increase the number of pipes in a bloc, for example, four pipes instead of three in each row for a total of eight tubes in a heat exchanger bloc. The number of turns can also be increased for one bloc of heat exchanger from five for the basic model to a maximum of seven or nine turns, but doing so will increase the overall length and mass of the heat exchanger. it is more rational to consider intensifying the heat transfer of the heat exchanger, for example by arranging the pipes not in a line but in a chess formation. The other methods for intensifying heat transfer than can reduce the temperature of the hot gas without increasing the overall mass of the heat exchanger have been discussed at the beginning of this section. The results from computational studies of various models of heat exchanger pipes which have increased surface area for heat exchange and their constructions which provide a significant intensification of heat transfer have been presented in section 3.2.

3.2. Study of different pipes for heat exchanger and their constructions to increase the heat transfer from the hot air.

The results of the tests performed in ANSYS CFX and the heat transfer analysis at the exit of the straight tube with different dimensions - 110mm and 800mm; having different shapes - cylindrical tube with a outer diameter of 6mm and an elliptical tube with an equivalent parameters of (7.3 * 4 mm), with a smooth inner surface without turbulizer and with a turbulizer [3] of height 0.3 mm. The relative cross flow diameter with the turbulizer is 4.8/5.4 = 0.89; the relative step size between adjacent turbulizer is t/D = 10.0/ 5.4 = 1.85. The optimum value as given in [3] is t/D=1.0. According to the experimental data given in [3] the inclusion of turbulizers in the heat exchanger in the internal surface of the tubes " ......volume of the heat exchanger reduces by approximately 2 times" [3] (Page 355, Figure 6.1 a). For all the calculations, the inlet temperature of the hot gas has been taken as 800°K.

Temperature of the cold gas flowing on the outside of the tubes has been taken as 450°K. This temperature corresponds to the temperature of the air exiting the compressor of the turbofan engine. The construction schematics of the turbine with the heat exchanger which is placed above the combustion chamber has been shown in Figure. 2. The results of the analysis of the afore mentioned variants have been discussed showing the temperature of the hot gas at the exit of the pipes.

Calculations have been performed for two variants with different lengths. The first variant is a pipe with a length of 110 mm, which corresponds to the height of the heat exchanger. The second with a length of 800 mm which corresponds to the total length of the pipes of the heat exchanger with four turning sections. The heat exchanger shown in Figures 2 and 5 have only 3 turning sections.

The following illustrations show the calculated velocity field of the hot air flow around a single cylinder in the transverse direction having a diameter of 6mm (Figure 6) and an oval having an equivalent dimension (7.3 * 4 mm) shown in Figure. 7.

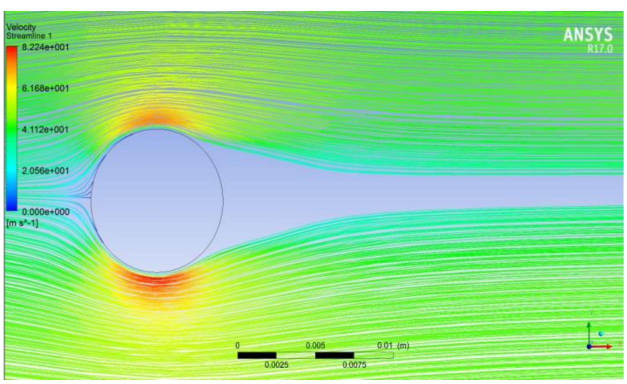

Fig. 6. Velocity flow field of the air flowing around a circular cylinder.

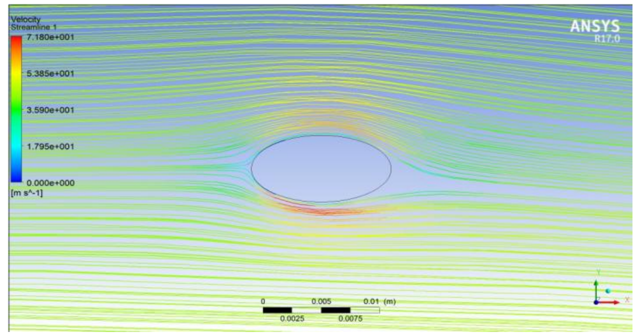

Fig. 7. Velocity flow field of the air flowing around an elliptical cylinder

As shown in the figures below the cooling air flows through a greater surface area of the elliptical tube before flow separation occurs thereby increasing the effective heat transfer surface area. Also heat transfer analysis has shown that the temperature drop on the inside of the tubes in the heat exchanger is not uniform. As it can be seen from the figures the centre is more heated than the peripheries of the tubes. However, as the equivalent height of the elliptical tube used in this case is a third less than that of a circle, the centre of the oval tube is heated more intensively. Therefore, the heat exchanger made of oval tubes should have a higher efficiency than a heat exchanger made of cylindrical tubes.

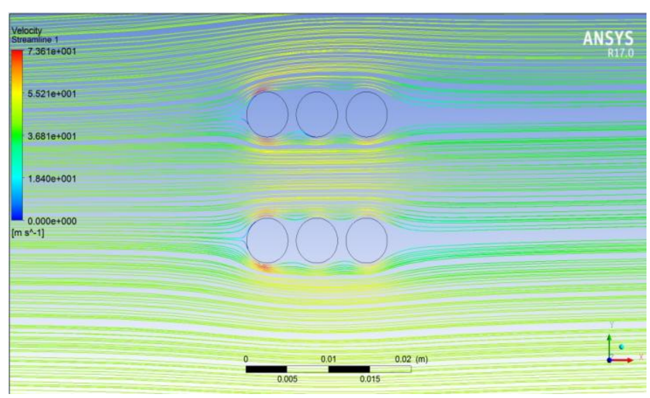

Fig. 8. Velocity flow field of the air flowing around circular cylinders arranged one behind the other in a row.

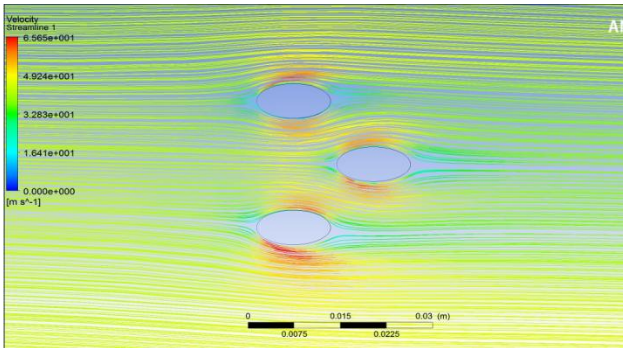

Fig. 9. Velocity flow field of the air flowing around elliptical cylinders arranged in a chess formation.

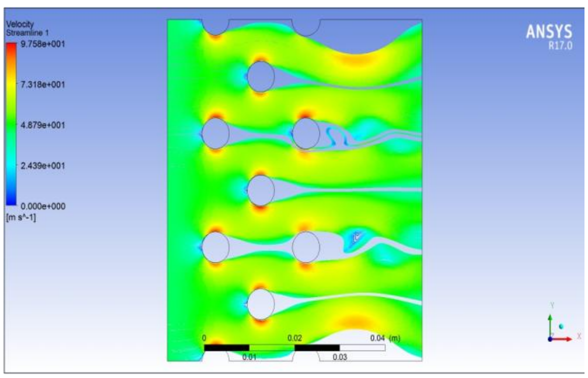

Fig. 10. Velocity flow field of the air flowing around circular cylinders arranged in a chess formation

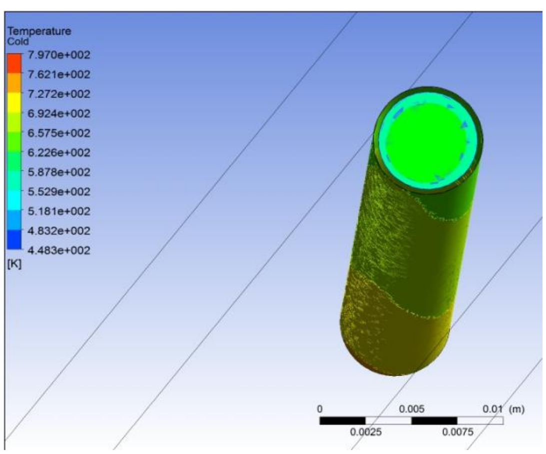

Fig. 11. Temperature field at the exit of the cylindrical tube of length 800mm, with cross flowing cold air at a temperature of 450°K

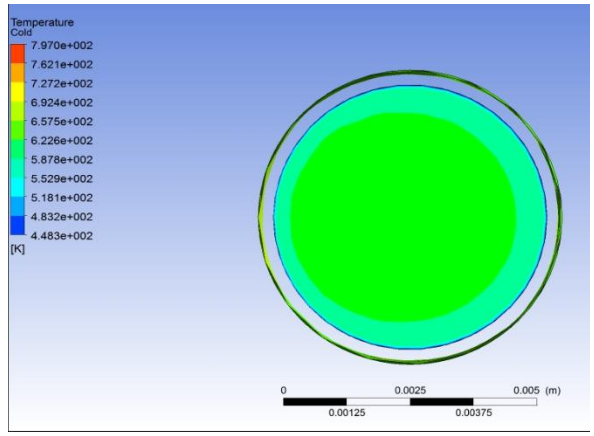

Fig. 12.Temperature distribution of the hot air at the exit of the cylindrical pipe of length 800mm.

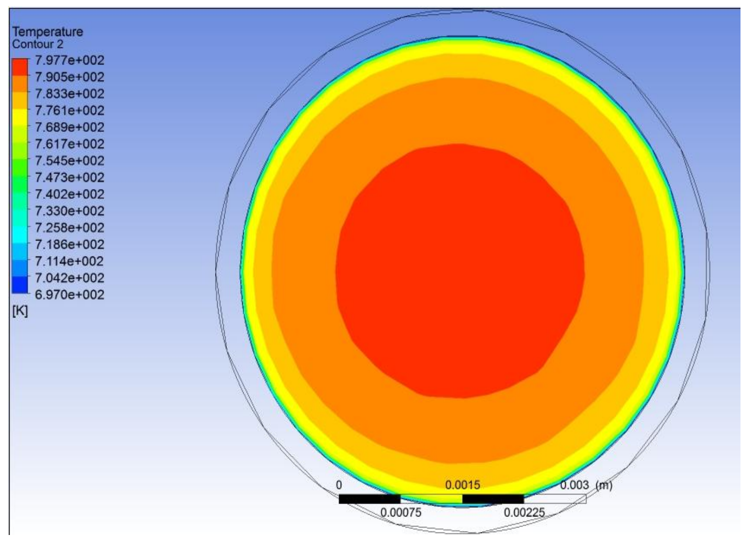

Fig. 13. Temperature distribution of the hot air at the exit of the cylindrical tube of length 110mm.

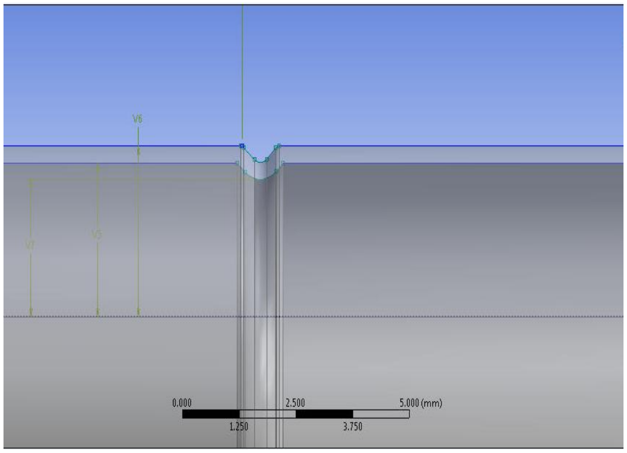

Fig. 14. Turbulizer installed on the inner surface of the tube at an interval of 10mm.

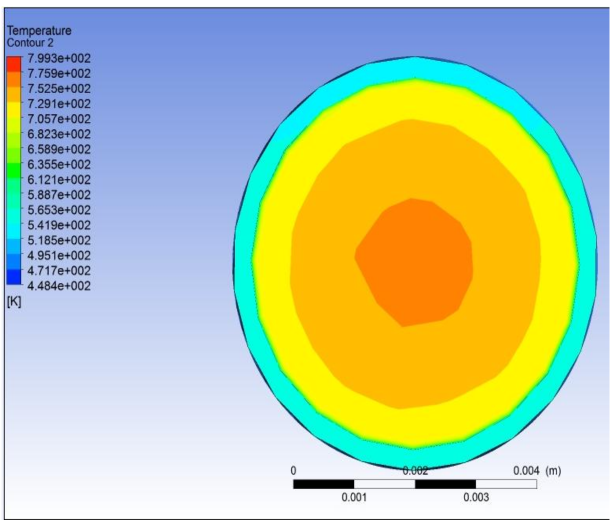

Fig. 15. Change in the temperature distribution after the usage of turbulizer for a cylindrical pipe of length 110mm.

As shown in Figure 15. the air near the walls of the tube is much colder than at the centre. It can be confirmed from this that the addition of a turbulizer results in an increase in cooling thereby increasing the effectiveness of the heat exchanger

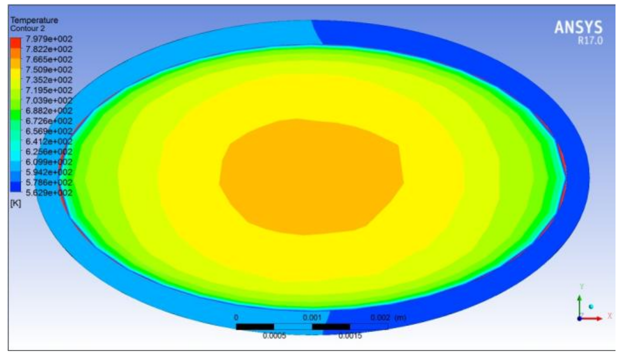

Fig. 16. Temperature distribution of the hot air at the exit of the elliptical tube of length 110mm.

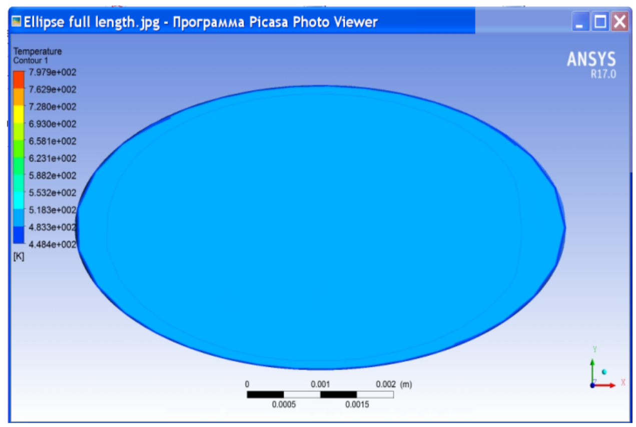

Fig. 17. Temperature distribution of the hot air at the exit of the elliptical tube of length 800mm.

Thus, the results of the calculations for straight cylindrical and elliptical tube presented from Figure 12 to 17 shows that for the same size of the perimeter and wall thickness, the intensity of the cooling of hot air in the oval tube is higher than that of cylindrical pipe by approximately 150 degrees. It should be noted that using a chess formation of pipes, the geometric dimensions of the heat exchanger as a whole only differs slightly to the currently used heat exchanger, and therefore it is possible to recommend this design of heat exchangers to be used in the cooling systems of modern and future turboprop and turbofan engines

Conclusion

The theoretical and experimental studies show that the tubular heat exchangers with smooth inner walls being used in turbofan and turboprop engines can have a significantly higher performance if they are manufactured with elliptical tubes instead of cylindrical tubes and with a turbulizer on the inner walls of the tubes to induce turbulence in the boundary layer. Thus it is of paramount importance that length of the tubes has to be determined in such a way that the hot air gets completely mixed inside thereby increasing the temperature drop inside the heat exchanger to a maximum value for that given configuration of the heat exchanger.

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