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COOLING OF EXHAUST GASES AS A POSSIBILITY TO INCREASE STEALTH PROPERTIES OF MILITARY HELICOPTERS

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Abstract

Helicopters, in comparison to other aircrafts, have much lower flight speeds and manoeuvrability, which makes them easy targets for actual combat assets like ground to air or air-to-air infrared-guided missiles. Current techniques aim to increase the combat effectiveness and lifetime of military helicopters performing combat missions by reducing the possibility of their detection on battlefield, thereby increasing their flight time without fire attack and reduce effects of potential strike. When designing new helicopter types, especially for combat applications, it is essential to pay enormous attention to infrared emissions of the solid parts composing the helicopter's structure, as well as to exhaust gases egressing from the engine's exhaust system. Due to their high temperature, exhaust gases, egressed to the surrounding are a major factor in infrared radiation emission level and, in consequence, detectability of a helicopter performing air combat operations. This article presents the possibility to decrease the infrared radiation level that is emitted to the environment by helicopter in flight, by cooling hot exhaust in special ejective cooler. Article presents also the exhaust cooler operation principles and results of numeric analysis of concept exhaust cooler adapted to cooperate with PA-10W turbine engine. Numeric analysis presented promising results in decreasing the infrared emission level by PA W-3 helicopter in flight, as well as increasing its stealth properties.

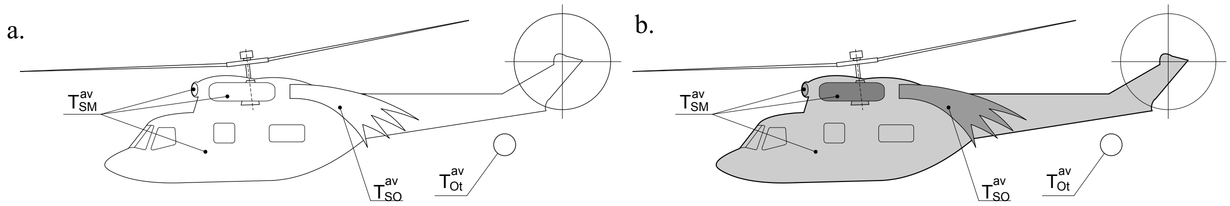
Keywords: *helicopter, exhaust, radiation, cooler, stealth*

1. Introduction

Low observable technology, widely known as stealth technology includes various methods in aim to make aircraft, ships, tanks, UAVs, missiles and other military objects less detectable on battlefield. This technology allows a potential intruder to enter enemy area undetected and deliver a first strike before the defender realizes he is being attacked or at least before, he has the time to respond effectively. Stealth technology is especially important in military aviation and allows reducing an aircraft's susceptibility to radar detection and mitigating its observable infrared, electromagnetic, visual and acoustic signatures. Stealth gives a clear and safe striking distance for the aircraft, enables the user to conduct surprise military missions, and ultimately results in an increase in its survivability. That technology cannot make an aircraft fully invisible but can highly reduce its detection range thus even if the stealth aircraft is detected, it cannot be easily engaged by a fire control radar or a missile radar seeker. All new aircraft types are designed taking into account low observable principles and techniques, while existing jet fighters and helicopters are considered for modification in order to reduce their radar and thermal signature [2, 9, 12].

While performing flight missions, helicopters emits to the surrounding electromagnetic radiation as well as infrared radiation with various wave intensity and various wave spectrum. When designing new helicopter types, especially for combat applications, it is essential to pay enormous attention to infrared emissions of the solid parts composing the helicopter's structure, as well as to exhaust gases egressing from the engine's exhaust system. Due to their high temperature and major amounts of carbon dioxide and water vapour, exhaust gases egressed to the surroundings are a major factor in infrared radiation emission and in consequence, detectability of a helicopter performing air combat operations. In case of thermal and radiation equilibrium between helicopter in flight and its surrounding, helicopter will become invisible in infrared (Fig. 1a) however it is only hypothetical case, impossible to achieve in real conditions. Emission equilibrium between helicopter, its exhaust and surrounding does not exist.

In reality helicopter temperature $\boldsymbol{T_{HA}^{Av}}$ and exhaust temperature $\boldsymbol{T_{ES}^{Av}}$ is higher than surrounding temperature $\boldsymbol{T_{SG}^{Av}}$, therefore thermal equilibrium between helicopter and its surrounding does not exist and helicopter becomes visible in infrared (Fig. 1b).



$I_{SM}^{Sr} \cong I_{Ot}^{Sr}, \lambda_{SM}^{Sr} \cong \lambda_{Ot}^{Sr}, T_{SM}^{Sr} \cong T_{Ot}^{Sr}, T_{SO}^{Sr} \cong T_{Ot}^{Sr}, \varepsilon_{SM}^{Sr} \cong \varepsilon_{Ot}^{Sr}, \varepsilon_{SO}^{Sr} \cong \varepsilon_{Ot}^{Sr}$ $I_{SM}^{Sr} > I_{Ot}^{Sr}, \lambda_{SM}^{Sr} \neq \lambda_{Ot}^{Sr}, T_{SM}^{Sr} > T_{Ot}^{Sr}, T_{SO}^{Sr} > T_{Ot}^{Sr}, \varepsilon_{SM}^{Sr} \neq \varepsilon_{Ot}^{Sr}, \varepsilon_{SO}^{Sr} \neq \varepsilon_{Ot}^{Sr}$

Fig. 1. Two characteristic cases of infrared radiation emission by helicopter in flight, a – helicopter almost invisible in infrared, b – helicopter visible in infrared [3, 4]

Intensity of heat exchange and by the same helicopter radiation level depends on the difference between helicopter temperature and surrounding temperature. With the growth of the temperatures difference, visibility of helicopter in infrared rises.

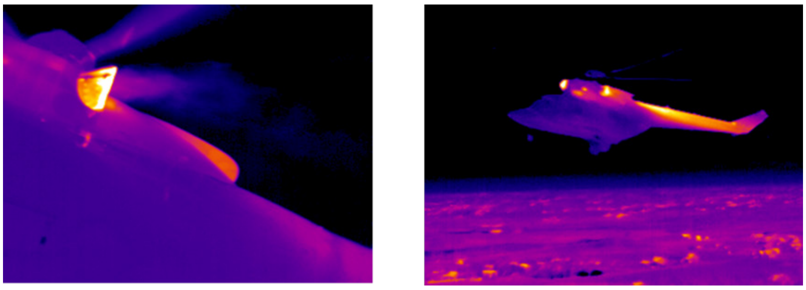


Fig. 2. Chosen frames from the video representing flight of the PZL W-3 helicopter in infrared [4]

Although the atmosphere provides some natural hiding places for aircraft, such as clouds and darkness, an airplane's signature must be lowered to survive in a battlefield environment.

2. Helicopter exhausts cooler operation principles

One of the most effective way to reduce the thermal sign of helicopter in flight is cooling of hot exhaust gasses, emitting from the engines to the atmosphere in special heat exchangers. Nowadays this process is realized in non-diaphragm coolers, where strong heat and momentum exchange between hot exhaust gases and cold air injected from atmosphere takes place. While mixing, agents exchange energy on the heat way, changing their enthalpy. Also, the chemical composition of the exhaust changes. In aviation, there are two types of non-diaphragm exchangers, namely:

- non-diaphragm exchangers in which both agents are introduced to a common mixing chamber with a conveying equipment like pumps, fans, or compressors,
- non-diaphragm exchangers in which one of agents (usually cooling) is introduced into the mixing chamber due to ejection process caused by flow of a second agent (cooled).

Ejective cooler is an automatically operating system, which work conditions directly depends on the engine work conditions. This results in closely connection between cooling intensity and the engine straining level in all helicopter manoeuvres. The main advantage of this type of coolers is high intensity of heat transfer that allows reducing their mass and dimensions.

An example of non-diaphragm exhaust cooler is HIRSS (Hover InfraRed Suppression System) that have been developed to reduce the infrared emissions of the exhaust from helicopter engines, such as the General Electric T-700 engine employed in helicopter designs such as the Black Hawk UH-60, the Apache AH-64 and the AH-1. Example of HIRSS used on AH -1 Super Cobra version was shown on Fig. 3, where the reflected thermal signature of tailboom was significantly decreased.

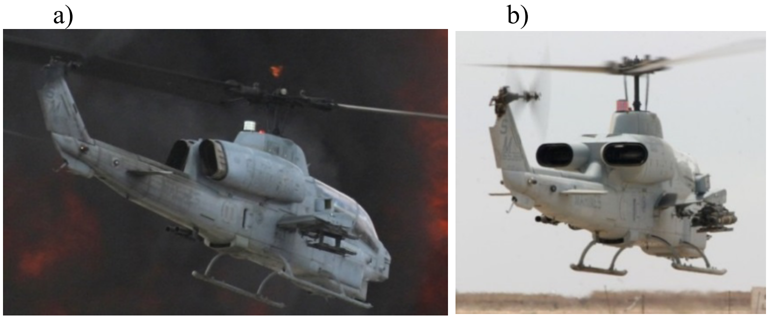


Fig. 3. AH-1 Super Cobra: a – without exhaust system modification, b – with HIRSS system [11]

The suppression system reduces infrared emission by recirculating hot engine exhaust gases within the suppressor core and mixing the heated gases with ambient air before discharging into the atmosphere.

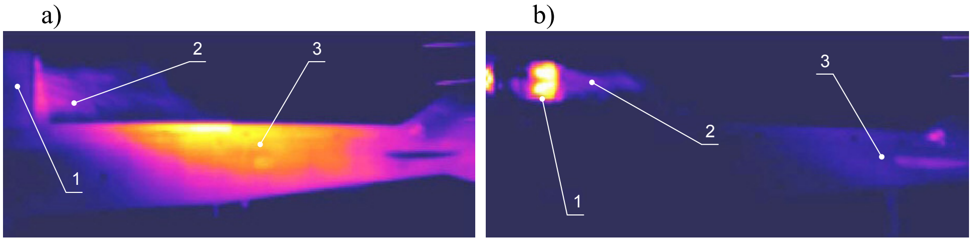


Fig. 4. AH-1 Super Cobra tailboom in infrared, a – without exhaust system modification, b – with HIRSS system: 1 – exhaust diffuser, 2 – exhaust gases, 3 – tailboom

Exhaust cooling system in AH- 64 Apache helicopter called Black Hole also works on the principle of atmospheric air ejection. The BH is a low-cost IR suppression system without any moving parts [7], as seen in Fig. 5.

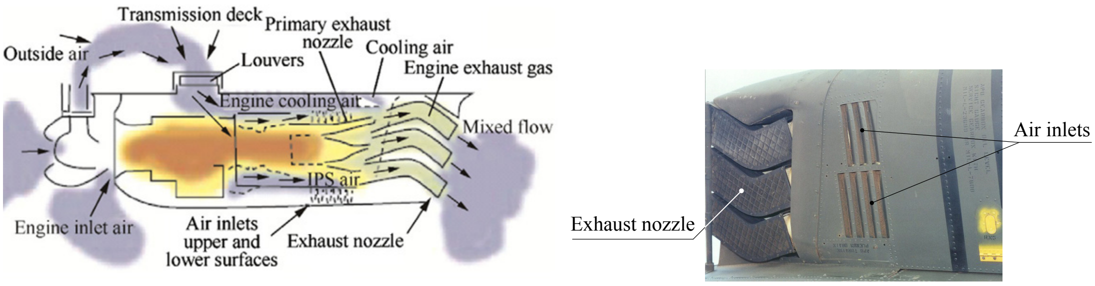


Fig. 5. Exhaust cooling system in AH-64 Apache [7]

The principle of system operation is directing the engine exhaust through special ducts that connect the engine exhaust stream with stream of a cold air passing over the helicopter. These channels ensure uniform outflow of exhaust stream, which gives a better heat dissipation effect by the air stream. The fresh air-stream dissipates the hot exhaust that emerges from the vents evenly, rather than allowing hot spots to appear. Also, before leaving the Black Hole system, air-exhaust mixture are directed through special insert made from heat absorbing material.

In order to additional improve the helicopter thermal sign reduction; ejected fresh air is used to cool both the engines and the transmission. The engine exhaust nozzles are angled outward from the airframe to better direct the output into the air-stream and they are cooled with outside air from rotor downwash (while hover manoeuvre) or with turbulent stream during the progressive flight.

Fig. 6. AH-64 Apache rear view, 1 – engine, 2 – exhaust cooler [14]

Mi -24 Hind is a Russian heavy attack helicopter. While war in Afghanistan, helicopters were modernized and they received complex self-defence systems. In the first phase, the thermal traps launchers (flares and metallic foil strips ASO-2W) were added. Helicopters were also equipped with distracting shields EWU, designed to cool the exhaust gases. EWU reduced the exhaust gas temperature from 500-600°C to 150-200°C and helicopter thermal signature up to 60%. Third system was the infrared active interference station Ł166W 1A.

Fig. 7. Mi-24 Hind helicopter after modernization, 1 – engine, 2 – exhaust cooler air intake, 3 – exhaust cooler [6]

Equipment of Russian helicopters in described devices caused in minor damage in the fighting in Afghanistan. Before modifications, the average accuracy of earth-to-air missiles were one of ten fired, after modifications just one of one hundred fired.

The most advanced low observable helicopter is prototype of RAH – 66 Comanche (Fig. 8). It is mainly made from composites and it is covered with radar absorbent materials. To reduce the radar cross-section, the all-composite fuselage sides are flat and canted, and rounded surfaces are avoided by use of faceted turret and engine covers.

Fig. 8. RAH-66 Comanche prototype in flight: 1 – engine air intake, 2 – exhaust cooler air intake, 3 – exhaust system [6]

The Comanche helicopter was equipped with an innovative method of infrared emission reduction, wherein the exhaust gases cooler is an integral part of the tailboom. In this embodiment, the exhaust outlet is disposed over the entire length of the tailboom providing fast, full and effective mixing of the hot exhaust gases and cold rotor downwash. The mixed exhaust is discharged through slots built into an inverted shelf on the sides of the tail-boom. Reduced infrared radiation by 75% in comparison to other helicopters in this class means that detect, track and destroy by heat-seeking missile is negligible. Because so thoroughly exhaust cooling, helicopter also does not need an interference transmitter active in the infrared.

3. Concept exhaust cooling system for PZL W-3 helicopter

The PZL W-3 Falcon is a Polish medium-size, twin turbine engine, multipurpose helicopter. Its structure characterizes high susceptibility to modernizations, so that currently helicopter exists in many varieties and various versions of development range.

Fig. 9. Helicopter in combat support version W-3PL Głuszec [6]

Despite many modifications, helicopter combat versions (W-3WA and W-3PL), still do not have sufficient protection in infrared. The helicopter is powered by two turbo-shaft PZL 10W engines installed in both sides of helicopter airframe. In general, concept helicopter exhaust cooler is formed by a modified turbine engine exhaust system, ejection chamber, mixing chamber and outflow diffusor. Exhaust gases outflowing from power turbine are directed through diffusor to nozzle where their static pressure is lowered below the atmospheric pressure. As a result of exhaust static pressure decrease and velocity increase, suction of cold air stream into cooler flow channel succeed. In the mixing chamber, two streams undergo intensive mixing where strong heat and momentum exchange takes place. As a result of mixing hot exhaust with cold air injected from surrounding new stream is generated with significantly lowered temperature and changed chemical composition.

Process of cold atmospheric air ejection into the cooler duct significantly depends on the static pressure level in engine exhaust system section. Application of nozzle in diffuser outlet section leads to static pressure decrease in engine outlet collector and consequently in cooler mixing chamber below the atmospheric pressure level. The lower static pressure in cooler duct the greater volume of external air ejected, and consequently increasing in efficiency of cooling.

Forming the turbulent streams geometry of exhaust and air mixture in ejective cooler duct is closely related to duct geometry, flow conditions of free exhaust stream moving in unlimited medium of air flow and differences between thermal states of exhaust and ejected air.

Especially good results in vortex path preparation are obtained by using the two-part turbulators. In this case, the dead zone after first obstacle is reduced and the vortex energy transfer is improved to the opposite turbulator side what facilitates the subsequent generation of next vortex. Concept cooler is equipped with one main swirler and two additional boundary layer swirlers. The basis for creation an experimental CFD model of exhaust cooler of the PZL-10W engine were the results of experimental tests on a helicopter W-3A Falcon in NOE flights presented in [5].

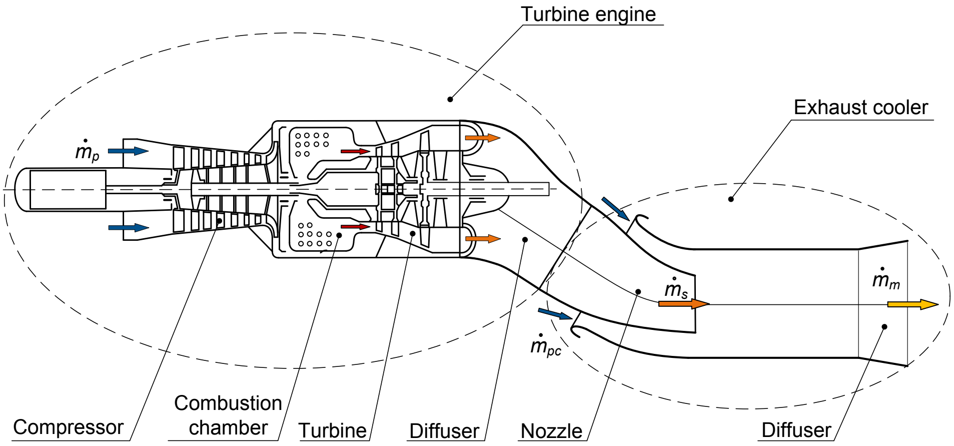


Fig. 10. Example of cooler built on to the PZL 10W turbine engine [6]

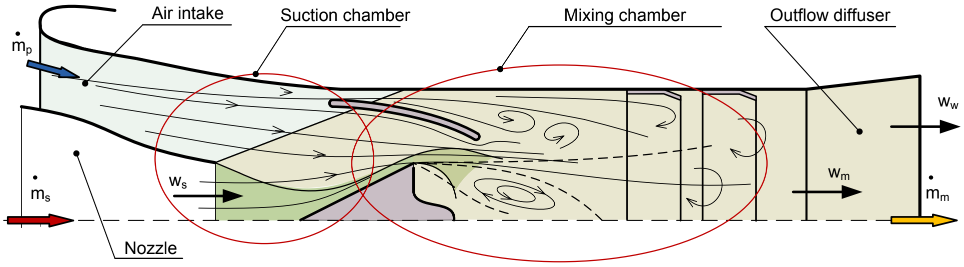


Fig. 11. Exhaust cooler flow channel equipped with swirlers [6]

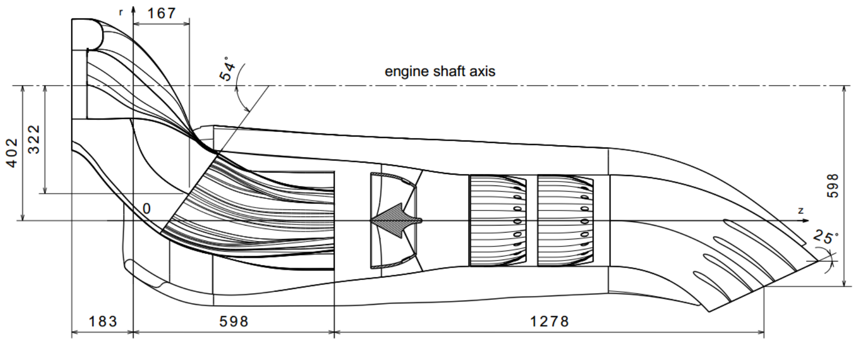


Fig. 12. Characteristic sections of exhaust cooler duct

Engine exhaust system of PZL W-3 helicopter was originally equipped in a diffuser with oval cross-section shape. Model was formulated taking into account the structural change of original engine exhaust system, in order to replace the diffuser to diffuser – nozzle system.

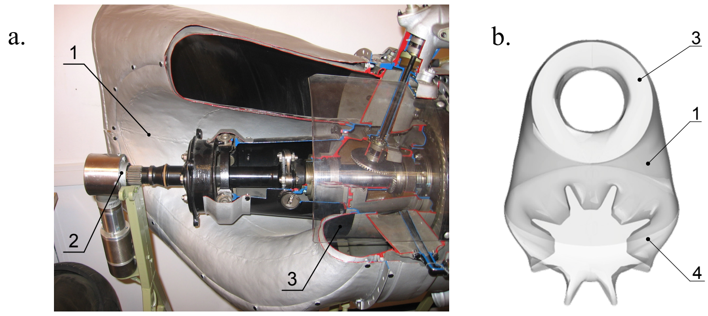


Fig. 13. PZL-10W engine exhaust system, a – classic version, b – modified version to cooperate with exhaust cooler:

1 – diffuser, 2 – drivetrain to main gearbox, 3 – exhaust intake, 4 – nozzle

This solution causes additional turbulence at nozzle outlet section and consequently increases in exhaust and air mixing level. Also, the contact area between external side of nozzle and flowing air increases what results in increase of heat transfer.

4. Computation method

Computational model includes the entire structure of concept cooler model with the geometry simplification in insignificant zones like sharp edges, chamfers and fillets at the air inlet (Fig. 5b). Referred elements have no significant impact on the calculation result though they significantly affect the size and quality of grid structure. Discretization of integration area was conducted using a spatial grid made of 9.000.000 tetragonal elements. The mesh was made as per instructions contained in [1], maintaining required quality, necessary to perform the correct numeric calculations. According to [5], in normal flight conditions each engine has an air mass flow of 2 kg/s and the exhaust gas temperature at engine diffuser cross-section of 662 K level. Those values were used as a part of boundary condition in numeric simulation. The cooling air parameters were set according to International Standard Atmosphere with reference to helicopter flight attitude at 100 m.

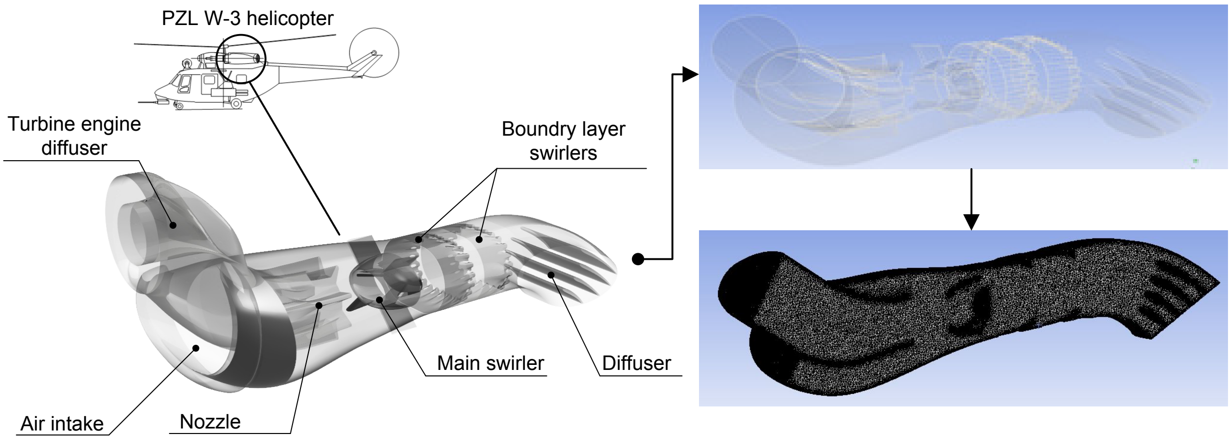


Fig. 14. Concept of PA W3 helicopter cooling system with mesh

Flow effects of air, exhaust gases, air-exhaust gases mixture and heat transfer between cold air and hot exhaust gases are given by differential equations of:

- mass transportation – flow continuity,
- ejection of cold air by expanding exhaust gasses,
- momentum conservation,
- energy,

and physical relationship equations. Formally, transport equations can be replaced with one equation in integral form:

$$\frac{\partial}{\partial t}\int_V \overline{\Phi}\, dV + \oint_S \overline{H} d\overline{S} = \int_V \overline{R}\, dV\,, \tag{1}$$

where $\overline{\Phi}$,$\overline{H}$,$\overline{R}$ are column vectors of state, convection and source column vector:

$$\overline{\Phi} = \begin{bmatrix} \rho \\ \rho \cdot \overline{v} \\ \rho \cdot e \end{bmatrix},\quad \overline{H} = \begin{bmatrix} \rho \cdot \overline{v} \\ \rho \cdot \overline{v} \cdot \overline{v} \\ 0 \end{bmatrix},\quad \overline{R} = \begin{bmatrix} 0 \\ \rho \cdot \overline{F} + \nabla \overline{T_c} \\ R_E \end{bmatrix}, \tag{2}$$

and R_E value is given by following equation:

$$R_E = \rho\bar{F}\cdot\bar{v} + \dot{\sigma} + \nabla(\bar{T}_c\cdot\bar{v} + \dot{q}), \tag{3}$$

where:
$\bar{v}$ – average gas velocity at specified location of turbulent flow,
$d\bar{S}$ – surface element vector,
$\bar{F}$ – mass forces,
$\overline{T_c}$ – total stress tensor (molecular and turbulent),
$\dot{\sigma}$ – intensity of internal heat sources,
$\dot{q}$ – external heat flux density.

The total stress tensor describes relationship:

$$\overline{T_c} = -p\cdot\bar{I} + (\mu_m + \mu_t)\cdot\left(2\,\bar{E} - \frac{2}{3}\nabla\bar{\mathrm{v}}\cdot\bar{I}\right), \tag{4}$$

where:
$\bar{E}$ – rate of deformation,
$\bar{I}$ – unit tensor,
μ_m, μ_t – dynamic coefficients of molecular and turbulent viscosity

The first lines of column-vectors are used to create integral form of mass conservation equation, second lines to momentum conservation equations and third lines to energy conservation equation. Hence the of momentum conservation, equation with turbulent stresses in vector form (Navier-Stokes equation) in integral form is as follows:

$$\frac{\partial}{\partial t}\int_V \rho\bar{v}\,dV + \oint_S \rho\bar{v}\cdot\bar{v}\,d\bar{S} = \int_V \rho\bar{F} + \int_V \nabla\overline{T_c}\,dV. \tag{5}$$

Presented set of Navier-Stokes equations do not have solutions in closed form formula, so additional functional relationships are required. Formula closing relationships between the Reynolds stress factors and averaged field effect parameters are defined by turbulence models. The exhaust cooler computation was performed in ANSYS Fluent 13 software with RANS (Reynolds Avaraged Navier – Stokes Equations) method. To simulate the turbulence, eddy viscosity was determined according to the two equation k-omega Turbulence Model. The closing equations were detailed in [10, 11].

4. Results and conclusions

The arms race creates ever newer and more technically advanced detection, observation, tracking and infrared homing missile systems. This forces aircraft designers to design and adapt counter solutions to reduce the risks and consequences of a potential strike. The detection of helicopters on the battlefield significantly depends of their emission of infrared radiation, as well as the methods, equipment and systems enabling their detection by the enemy. Modern missiles equipped with guidance systems for the source of infrared radiation are one of the most important threats to helicopters performing combat missions. The infrared suppression systems increase the aircraft's survivability by reducing the opportunity for an infrared seeking threat system to acquire, lock onto, track, and destroy the helicopter. Because of a high temperature, cooling of exhaust gases is a major tactic in aim to decrease infrared emission by helicopter in flight, as well as to improve the stealth properties.

Presented results show possibility to significant reduce of the infrared emission of PZL W-3 helicopter and exhaust cooling method as a one of the most important of passive protection system of helicopter in flight. Static temperatures distribution, especially in outlet cross-section presents significant cooling process that allows reducing outflowing gas mixture temperature up to 32%. For example, the scale of static temperatures in the cooler outlet-section is approximated at Fig. 15.

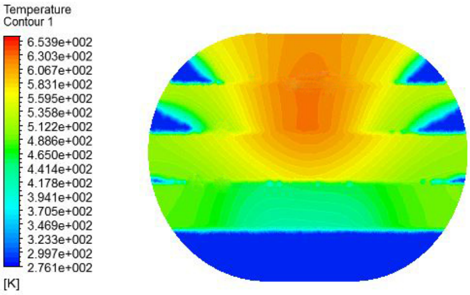


Fig. 15. Distribution of temperature at outlet cross-section of cooler

The average temperature at the outlet cross section is reduced from 662 K in normal exhaust system to 450 K.

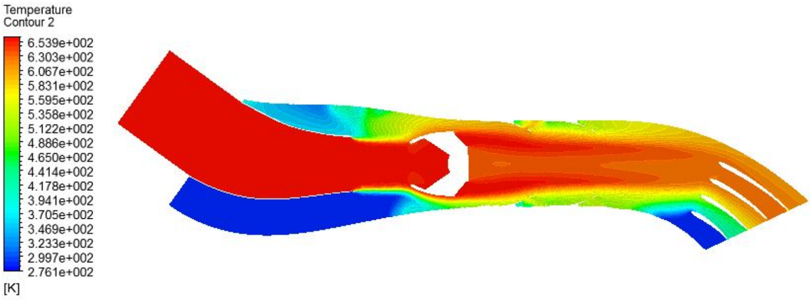


Fig. 16. Distribution of temperature inside cooler flow duct

The spatial distribution of temperature inside the cooler flow duct was shown in Fig. 17.

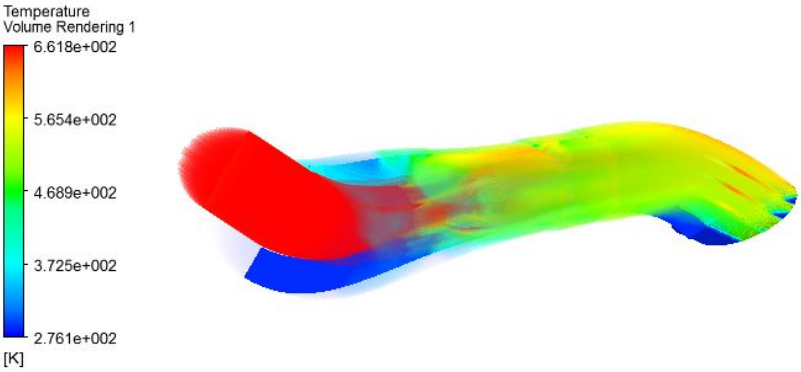


Fig. 17. Spatial distribution of temperatures in cooler flow duct

Presented numerical modelling method and simulation results are considered as initial to the final version of the computation program. In future, it is necessary to pay attention at areas with a lower mixing intensity (including the mixing chamber). It is expected that this observation will facilitate the introduction of appropriate changes in the structure of swirlers' geometry in order to improve the mixing conditions in these areas. Also, the influence of main rotor downwash to air intake of cooler is necessary to consider, as well as heat transfer through the cooler walls.

References

[1] Ansys: *Modeling Turbulent Flows*, Introductory FLUENT Training, 2006.

[2] Grant, R., *The Radar Game Understanding Stealth and Aircraft Survability*, Mitchell Institute 2010.

[3] Groninga, K., *Development and implementation of the H-1 turned exhaust system*, AHS, Texas 2005.

[4] Fijałkowski, S., *The Experiment – Based Analysis of the Infrared Emission by a Helicopter in Flight*, IBTL Reports, Warsaw 2011.

[5] Fijałkowski, S., *Performance model of turbine engine exhaust cooler in extreme conditions helicopter flights, Part 1, Identification of membranneless exhaust gas cooler interaction with the helicopter turbine engine,* IBTL Reports 194-195, Warsaw 2008.

[6] Paszko, M., *Analysis of the influence of swirls in ejective helicopter cooler on the process of cooling of exhaust gases emitting into the atmosphere*, Master Thesis at Lublin University of Technology, Lublin 2015.

[7] Pan, C., Zhang, J., Shan, Y., *Progress in helicopter infrared signature suppression Chinese Journal of Aeronautics*, 27(2): 189-199, 2014.

[8] PZL-10W Engine, *Technical Characteristics*, WSK, Rzeszów.

[9] Vass, S., *Stealth Technology Deployed in battlefield*, AARMS, 2003.

[10] Wilcox, D. C., *Formulation of the k-omega Turbulence Model Revisited,* AIAA Journal, Vol. 46, No. 11, pp. 2823-2838, 2008.

[11] Wilcox, D. C., *Turbulence Modeling for CFD*, 3rd edition, DCW Industries, Inc., La Canada, CA 2006.

[12] Zikidis, K., Skondras, A., Tokas C., *Low Observable Principles, Stealth Aircraft and Anti-Stealth Technologies*, Journal of Computations & Modelling, Vol.4, No.1, 129-165, 2014.

[13] Internet sources: www.aircav.com/cobra/ahgal24/ah1w-070517.html; www.richard-seaman.com/Wallarticle/Aircraft/Helicopters/SuperCobraAndWallOfFire_1.jpg