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MEASURING TEMPERATURE DISTRIBUTION ON THE SURFACE OF FLYING MISSILES

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Abstract

There are problems associated with flight of objects such as rockets after exceeding sound barrier. One of them is heating up their body during the flight, especially at low altitudes. Overheated surface of rocket leads to serious consequences, such as rapid destruction of material components of missile. It could cause an interference with target tracking signal if it is on the spectral range of missile optoelectronic detecting head. It can cause destruction of flying missile in extreme cases. In addition, temperature increase causes an increase of drag force of object what directly influences its ballistic parameters. The subject of the paper is to present a concept of experimental set-up to test the heating of missile body at flight. The set-up is based on a wind tunnel. Four missiles were selected for initial analysis in order to test some typical designs for significantly different flight velocities and aerodynamics.

Boundary layer at flow around the surface, determining temperature field of missile, the local distribution of heat transfer coefficients on the sphere and exemplary distribution of temperature and pressure on the sphere during flow around, distribution of Nusselt numbers for different velocities of flow around roll, numerical model of rockets, distribution of Mach number, temperature field and velocity vectors are presented.

Keywords: *missiles, wind tunnel, thermal field, boundary layer*

1. Introduction

The atmosphere affects a missile moving in space. Results of these interactions are both useful and negative forces acting on rocket. Aerodynamic lift is undoubtedly a favourable factor whereas the air drag is an unfavourable one. In the definition of resistance caused by pressure forces acting on the body, the most important action narrows to boundary layer or thickness of stream where velocity of flow around varies from zero to a specific velocity. It is area of viscous fluid and heat conducting near flow around the surface. In this area, both gas velocity and temperature changes in direction normal to the body. These two factors determine transfer of momentum and heat.

It is a fact that friction stresses are significant even at low viscosities because velocity gradients in flow around are large. Viscous forces are comparable to inertial forces of fluid.

Distribution of temperature field in the body depends among other things on type of flow around. It can be divided into laminar, transitional and turbulent flow around (see Fig. 1). We determined degree of turbulence in an interval. It is determined by corresponding Reynolds number Re, which is function of characteristic length L, speed of flow around the body V and kinematic viscosity ν:

$$\mathrm{Re} = \frac{V \cdot L}{\nu}. \tag{1}$$

Study of above-mentioned problem is very important because of consequences that may arise with poorly treated heating problem for missiles in flight. The consequences may be such as the damaging or even destroying missiles in flight. In addition, increase of temperature has influence on loss of ballistic parameters. For example, when air speed is about 555 m/s the surface temperature of the rocket body may exceed 100°C and at 695 m /s, it is above 170°C.

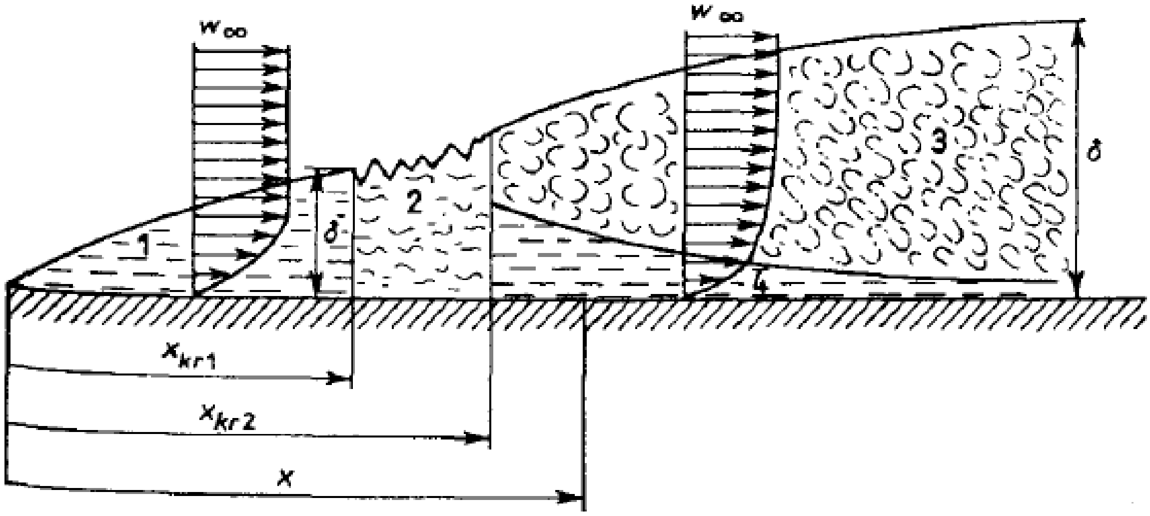

Fig. 1. Boundary layer at flow around the surface [1]

2. Problem of determining temperature field of missile

Rocket missile consists of three basic elements: nose, part of cylindrical body, steering and stabilizing planes. For simplicity, the paper shows the determination of the temperature field of cylindrical section and nose which in simplest case is in form of a sphere.

On the sphere symmetrically to point of ram effect the thickness of laminar boundary layer increases in direction of its flow around and at the same time, the heat transfer coefficient decreases up to a point of detachment. If the sphere is connected with cylinder part, the separation occurs in the middle of its diameter in direction of incoming stream. Heat fluxes transmitted by fluid are contained between radius from $d/2$ to ∞ and heat-acquired surfaces of the sphere are:

$$\dot{Q} = \frac{4\pi\,\lambda\,\Delta T}{0.5\,d}, \quad \dot{Q} = \alpha\,\pi d^2 \Delta T \;\rightarrow\; \alpha = \frac{2\lambda}{d}. \tag{2}$$

In this case, a threshold value of the Nusselt number on entire surface for Re → 0 is $\overline{(\mathrm{Nu})} = 2$, but this number can be determined on basis of experimental tests obtained e.g. by Withaker's:

$$\overline{\mathrm{Nu}} = 2 + (0.4\,\mathrm{Re}^{0.5} + 0.06\,\mathrm{Re}^{2/3})\,\mathrm{Pr}^{0.4}(\mu_P/\mu_s)^{0.25}. \tag{3}$$

Applied within $3.5 < \mathrm{Re} < 8 \cdot 10^4$, $0.7 < \mathrm{Pr} < 380$ and $1 < (\mu_P/\mu_s) < 3.2$.

This phenomenon for a roll is more complicated because it is the main part of missile body. Flow around can change in very different ways for its total length. Consideration should be paid to airflow interference between the roll and lifting surfaces. In addition, body may include various elements e.g. fastening for rocket launcher that may introduce additional disturbances. Rocket propulsions are also in roll, which additionally increases its temperature. Apart from analysing a/m elements, the temperature field on the surface of the roller should stabilize and be lower than for the head part as there is "no ram effect point".

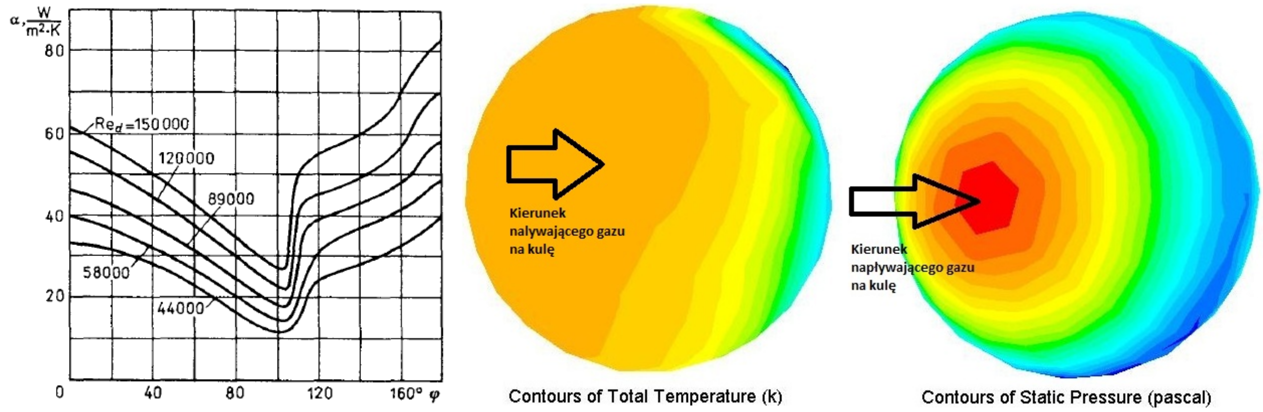

Fig. 2. The local distribution of heat transfer coefficients on the sphere [1] and exemplary distribution of temperature and pressure on the sphere during flow around

In such case, the fluid flows around the roll with parallel speed to its axis. For large Re numbers distribution of Nusselt number on circuit of the roll has two minimums connected with separation of the boundary layer. In this case the Nu number can be defined according to proposal of Churchill and Bernstein for $10^2 < \mathrm{Re} < 4 \cdot 10^7$ and $\mathrm{Pr} > 0.2$.

$$\overline{\mathrm{Nu}} = 0.3 + \frac{0.62\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/2}}{\left[1+\left(\frac{0.4}{\mathrm{Pr}}\right)^{2/3}\right]^{1/4}} \left[1+\left(\frac{\mathrm{Re}}{282000}\right)^{5/8}\right]^{4/5}. \tag{4}$$

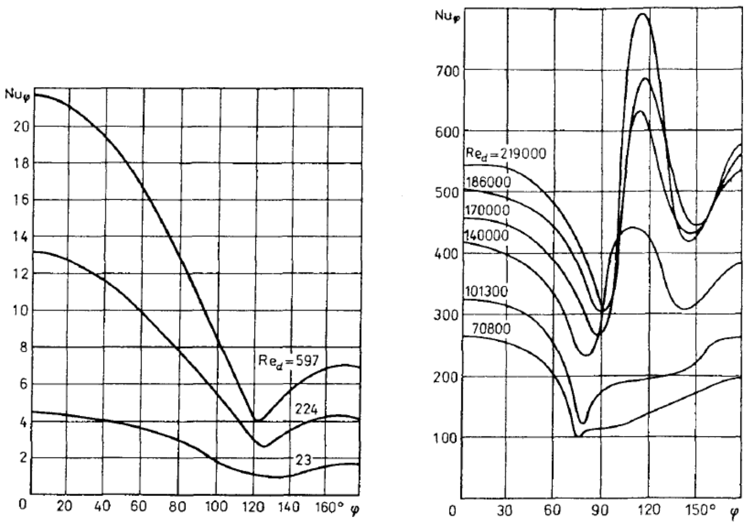

Fig. 3. Distribution of Nusselt numbers for different velocities of flow around roll [1]

Nusselt number is criterion of similarity and it defines a relation of heat exchange rate in result of convection to heat exchange rate in result of heat conduction. An example of its distribution on the roll is showed in the next paragraph.

3. Numerical simulation

Four models of rockets (Fig. 4) with different constructions and ballistic parameters were prepared to numeric simulation. The idea of an approach is to analyse different solutions to study their heating during the flight. In the result it will be assessed the unification of developed mathematical model of rocket missile taking into account the temperature in models of equations both for motion and aerodynamic loads.

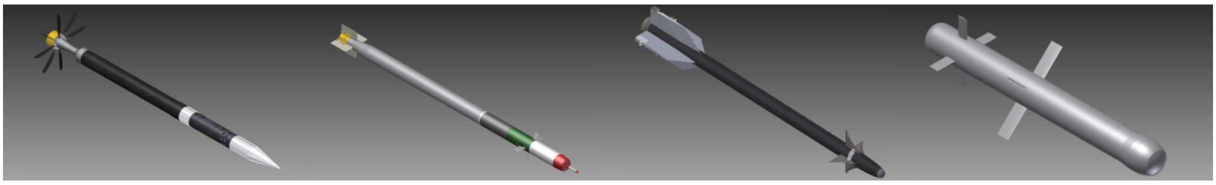

Fig. 4. Numerical model of rockets

The real models of rockets were also created to carry out experimental test on set-ups. The experiments with using thermal cameras can permit to receive real results with acceptable level of errors. In the next step, these results will be compared with data received in numeric simulation and used for developing an advanced mathematical model and optimization of chosen construction. Fragment of missile model prepared to testing is shown in Fig. 5.

Fig. 5. Selected example of model for testing temperature field in tunnel [3]

Basing on a specific construction a distribution of surface temperature field can be expected but its values remain unknown as they depend on different factors. Some of them were mentioned earlier. The most heated fragments of flying object construction are places of gas ram effect. The set-off components, asymmetry, protuberances as well as nasal part of missile fall also in this category. It is where some solutions could be found to reduce the heating of missile. The second domain in which we can lower temperature is selection of adequate construction materials for rocket body. The use of proper materials depends first of all on flying velocity, because the velocity is a temperature function. It is connected with the resistance and thermal energy dissipation during flight. An example of heating of missile is presented in Fig. 6.

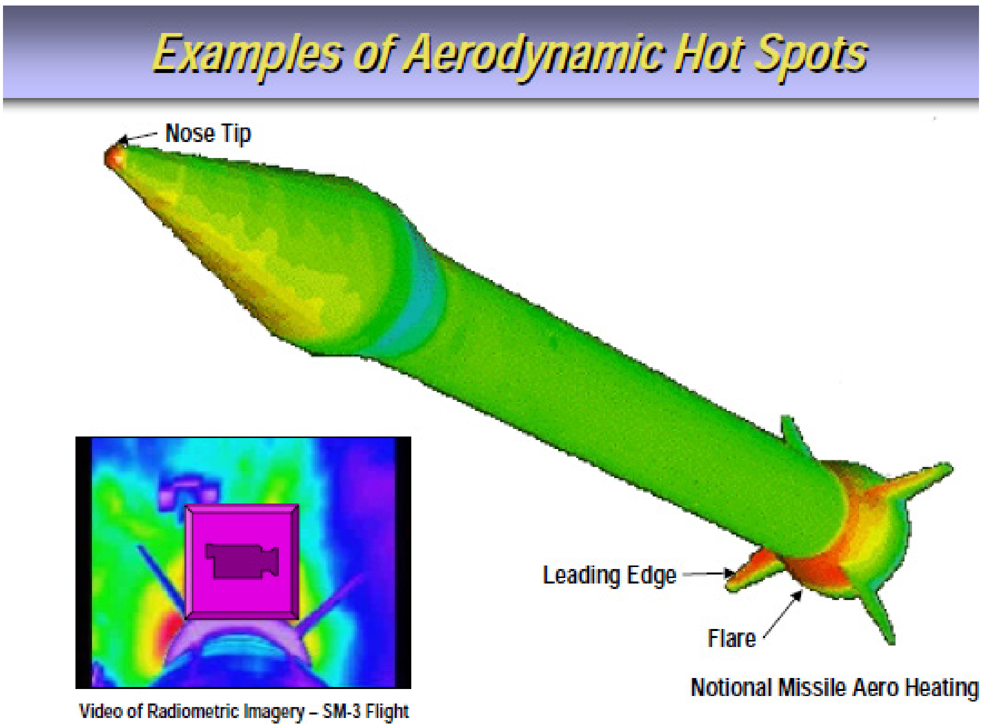

Fig. 6. Example of temperature distribution on rocket body [2]

High temperature on body in places of ram effect in nasal part and near stabilizers are very good visible in Fig. 6. The confirmation of back part heating is visible on video film of IR camera pictures. It may be concluded on the base of temperature distribution that presented missile moves in atmosphere with relatively high speed. For missiles, moving with lower velocities, which do not cross 0.7 Ma it is a different case. Such missile is presented in Fig. 7.

Fig. 7 Model to ballistic testing of ground – ground class missile [3]

The model of missile used as an aerial target is presented (Fig. 7) as an example. We have not complete computer model on present stage of work because temperatures resulting from burning propellant of sustainer rocket engine were not considered. However, this element can be skipped because time of work of this engine is out below one second. More essential is the body heating on result of flares combustion that simulates the aerial target. This element will be analysed in future work. A study will be carried out to optimize the body concerning the distribution of temperature field by minimization of impact of the most negative factor. Temperature field versus the speed of rocket (Fig. 8) is shown in Fig. 9.

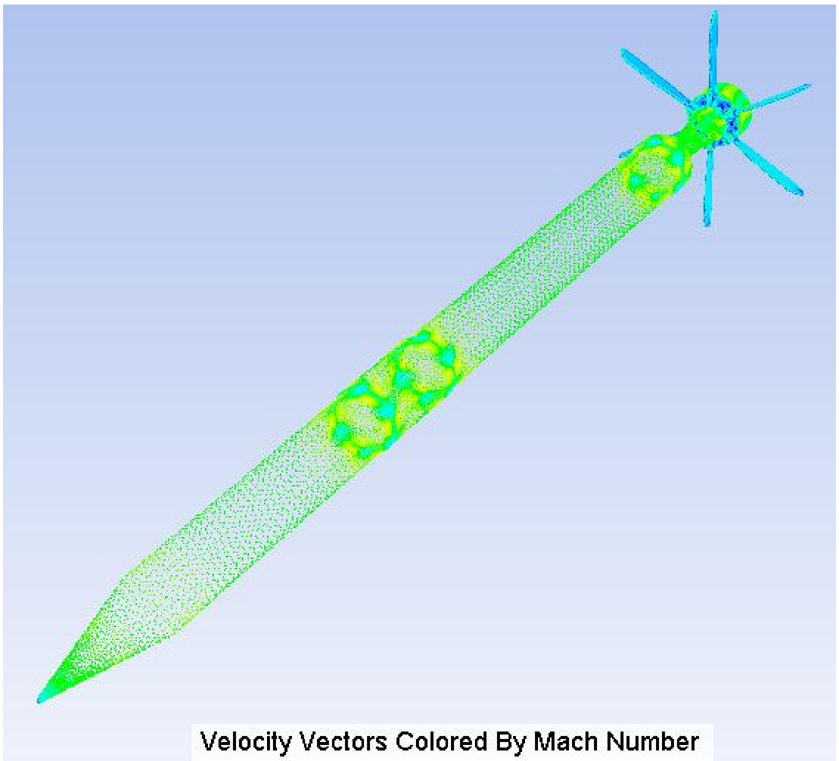

Fig. 8. Distribution of Mach number on body of rocket

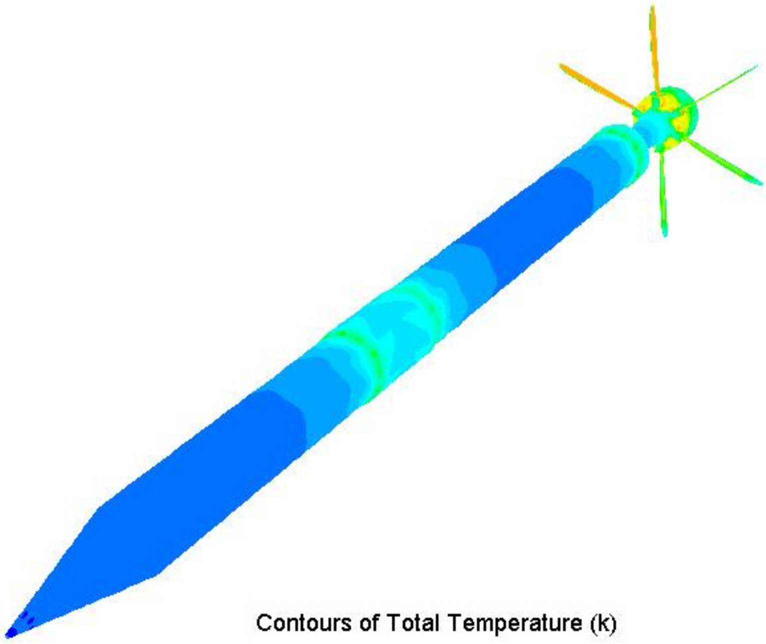

Fig. 9. Distribution of temperature field on body of rocket

On body of rocket, there is a visible considerable growth of temperature in points of ram effect consisting of rocket launcher leading ring and stabilizer nozzle where "perpendicular wall" produces a large resistance. Difference between diameter of rocket and ring is about two millimetres.

Distribution of temperature on body is about several ten degrees and therefore for velocity below 0.7 Ma the front part of rocket is cooler than its rear part (blue colour – Fig. 9). It is well visible on stabilizers that different temperatures are on two different sides. This is due to the fact that by introducing the stabilizers the object rotates and the stabilizers are tilted at an angle to incoming air stream. Therefore, at greater resistance the higher temperature appears (orange colour) and on the other side the lower (green colour). This is because velocity is not high. At supersonic velocities, the thin plate stabilizers are heated uniformly and have a uniform colour appropriate to temperature on the surface.

In the next example (Fig. 10), we show that the highest temperature is mainly located on the front surface of missile.

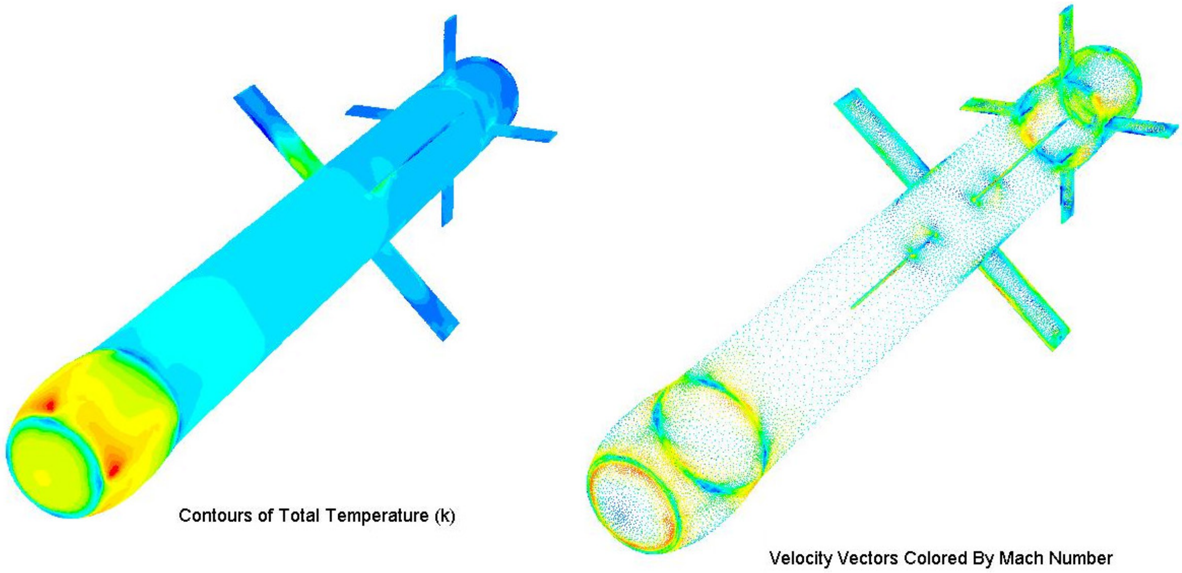

Fig. 10 Distribution of temperature field and velocity vectors on ground-ground rocket

4. Conclusions

A preliminary numerical analysis shows that although missiles are similar in body structure but each is significantly different considering its both aerodynamic loads and heat. This conclusion reflects the fact that the most optimal design minimizing negative effects on objects has to be found. It is all possible because every design is a combination of various compromises.

The analysis shows that the most vulnerable elements on flying objects are the elements protruding from body and the front part. Of course, it is intuitively sensed, however the awareness of this fact will better optimize the structural design of the body. It is important to know temperature values at any given point because sometimes it is acceptable in particular cases when temperature does not greatly affect the flight. This applies mainly to low- velocity flight, i.e. below Mach number.

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