DOI: 10.13009/EUCASS2017-371

Hybrid LES-RANS simulations of enthalpy reduction in T-shape chamber by means of transverse cold air injection

A.Y. Iakovchuk and O.V. Guskov**

*Central Institute of Aviation Motors n.a. P.I. Baranov(CIAM), Moscow, 111116, Russia

Abstract

The minimum enthalpy of arc-jet produced in high-enthalpy flow generator is in a range of 10…20 MJ/kg. Gas enthalpy reduction down to 3…5 MJ/kg is achieved in mixing chamber - the essential unit of arc-heated wind tunnel facility. The mixing chamber has a T-shape and connects 2 arc generators and nozzle throat section. Multiple orifices for cold gas transverse injection are implemented. The numerical prediction of mixing efficiency and flow parameters on the outlet is the main objective of current research. CFD simulations using IDDES hybrid RANS-LES model are presented. Species diffusion and chemical reactions with NOx formation are considered.

1. Introduction

The limitation of minimum enthalpy at the arc-heated generator linked to minimum allowable current necessary to sustain the electrical discharge. High-temperature nitrogen flow with enthalpy 10...20 MJ/kg produced in generator. This corresponds to mean gas temperatures of 6000...7000 K. High-enthalpy synthetic air flow is produced in the mixing chamber by means of ambient temperature oxygen injection. Schematic view of mixing chamber is presented on Figure 1. Basic scheme of lowering enthalpy is transverse cold gas injection. This scheme is used for enthalpy reduction in SCIROCCO plasma wind tunnel as described in [2]. Mixing chamber has two 100 mm diameter inlets where high-enthalpy gas enters, then two injection sections where series of small-orifices introduced for ambient temperature oxygen injection. Then, T-joint is formed to connect two mixing streams inside 150 mm diameter fine mixing pipe. At the end of mixing chamber nozzle throat section is connected. Complete design of developed mixing chamber is represented on figure 2.

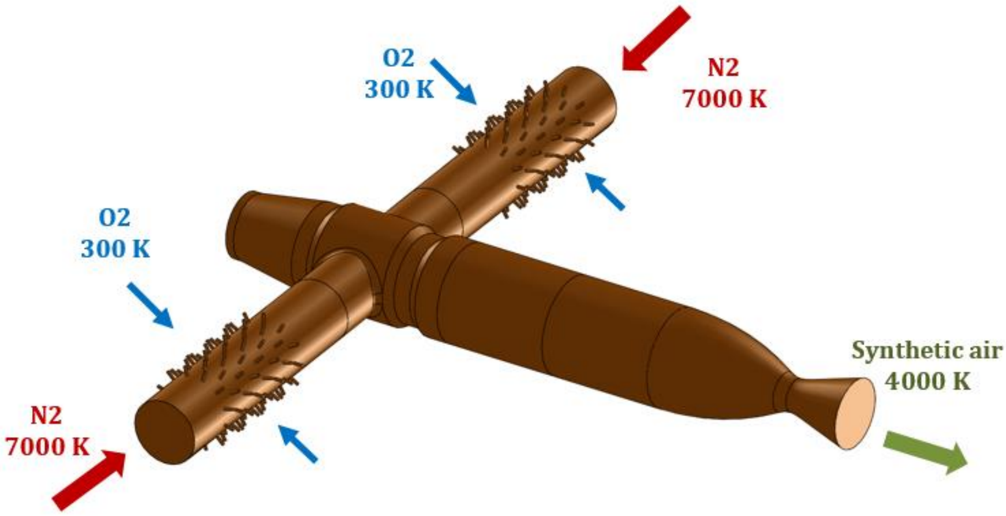

Figure 1: Schematic diagram of mixing chamber

During mixing process various aspects should be considered. The desired operating regimes varies in 1…15 MPa pressure range with temperature of outflow around 4000 K. Depending on operation regime, from 20 to 70% of gas mass flow rate comes through cold injection sections. If needed for achieving outlet gas composition close to air, ambient temperature nitrogen supplied through injection sections as well.

DOI: 10.13009/EUCASS2017-371

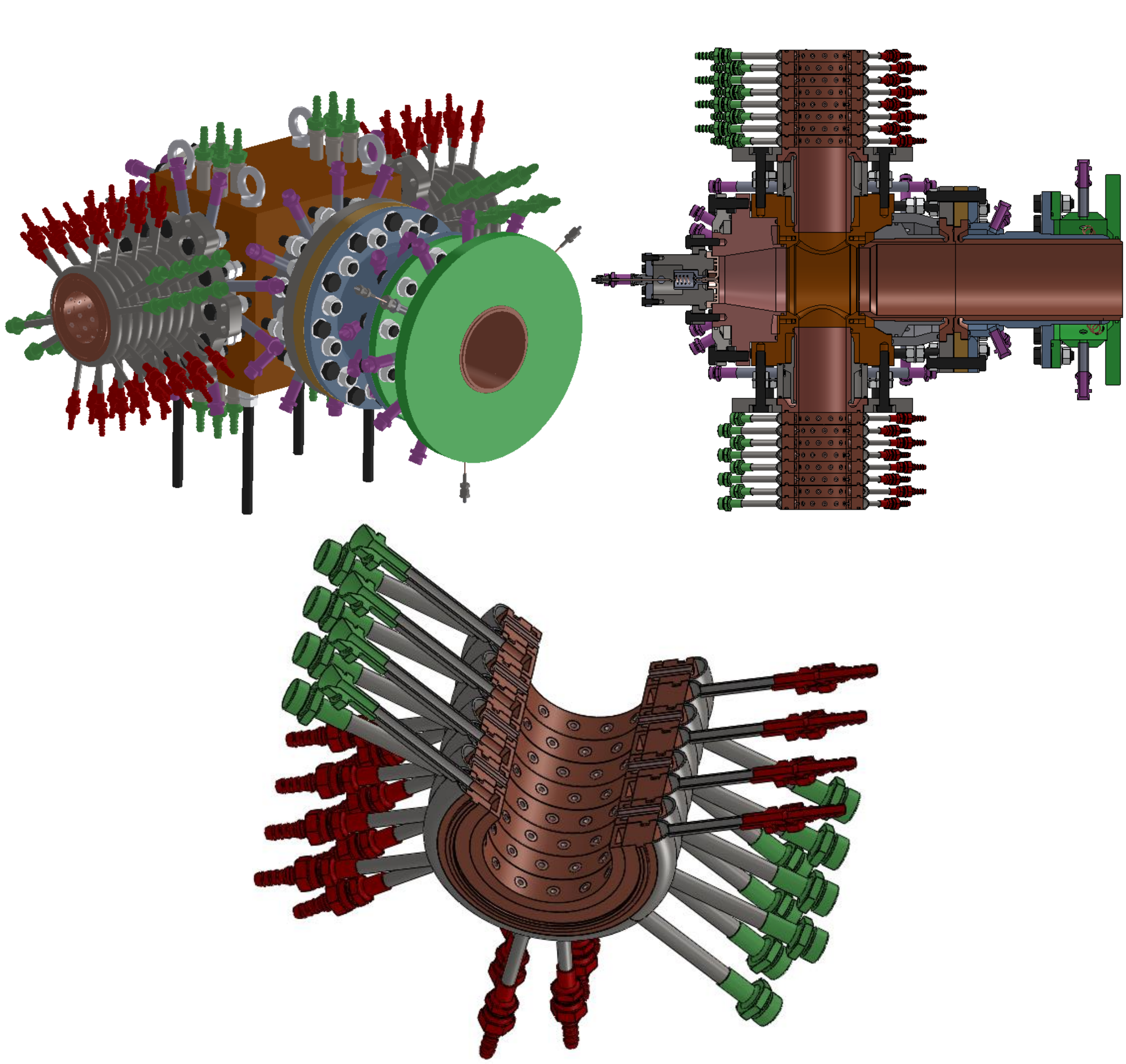

Figure 2: Design of T-shape mixing chamber and design of cold gas transverse injection section

As shown in [2], the strength of the cold air jet requires a careful calibration. If the transverse injection strength is too low, the cold air doesn't reach the injection chamber centreline and will remain near the walls. Otherwise, cold gas may tend to occupy centreline region of the chamber while high-enthalpy gas being displaced toward periphery. A simple equation that represents the trajectory of transverse gas jet is derived in [3]:

$$\frac{y}{d_j} = 1.92 \cdot q^{0,335} \cdot \left(\frac{x}{d_j}\right)^{0,33} \tag{1}$$

This formula is presented in x-y coordinate plane, where x – direction along the high-enthalpy flow, y – perpendicular direction where ambient temperature gas is injected. Quantity d_j is the orifice diameter. Parameter q represent the ration of flow momentums:

$$q = \frac{\rho_j U_j^2}{\rho_\propto U_\propto^2} \tag{2}$$

where ρ – density, U – velocity, index j is relevant to cold transverse jet and index ∞ is for the primary flow. Based on this formula, operating regimes may be calibrated and cold gas may be redistributed as desired between many cold injection collectors.

DOI: 10.13009/EUCASS2017-371

2. Numerical modelling approach

Uniform temperature and species profile is required at the mixing chamber outlet. Mixing efficiency and flow composition is of major importance for producing qualitative experimental conditions and reliable understanding of experimental results. Along with O2 and N2 components, for the outflow temperatures in range of 3000…7000K considerable dissociation and NO formation is of serious concern. As shown in [4], up to 10% NO mole fraction may be present in the flow.

Regime calibration for mixing chamber includes several steps. For the first estimation, cold gas mass flow rates are calculated based on experiment requirement and redistributed in injection collectors based on formula (1) so that cold jet strength is enough to reach plenum centreline. Then, simulation of simplified geometrical models with one cold injection and one full collector, combined from 8 orifices, is performed. Then, numerical simulations of injection section and full-complexity model of T-shape chamber is performed for some most desired operating regimes. As long as flow inside mixing chamber is highly turbulent, with many interacting jets, chemical species reacting in vortexes, LES-based turbulent model is applied. RANS approach has been tested as well but it doesn't provide sufficient information for mixing efficiency, so not presented. IDDES model with 2-nd order time and space discretisation and kw-SST RANS submodel is used.

For preliminary simulations only 2-species simple mixture model is applied, representing O2 and N2 species. This simulation doesn't consider chemical reactions and deals only with diffusion and thermal conductivity. For dissociation and NOx formation estimation, eddy dissipation concept model is used to calculate chemical reactions. Transport properties and thermodynamic data are imported in a range up to 20000 K [6]. Reaction mechanism is introduced in CHEMKIN format. For the current simulations the model includes following 6 species: O, N, O2, N2, NO, NO2.

Following reactions was taken from Jachimovski [5] mechanism for air-hydrogen combustion with N2 participation (all reactions without H component considered):

Table 1: Reactions considered in simulation

O+O+M=>O2+M	N+O2=>NO+O	O+NO2=>NO+O2
O2+M=>O+O+M	NO+O=>N+O2	NO+O2=>O+NO2
N+N+M=>N2+M	N+NO=>N2+O	NO2+M=>NO+O+M
N2+M=>N+N+M	N2+O=>N+NO	NO+O+M=>NO2+M

Although using that considerably simple kinetics is required following validation for high-temperature applications, for the current development stage this helps more carefully estimate mixing process and flow parameters. Equilibrium species concentrations for applied reaction mechanism was calculated using CHEMKIN and presented on Figure 3. As presented, NO concentration reaches maximum of 10% near 4000…6000 K.

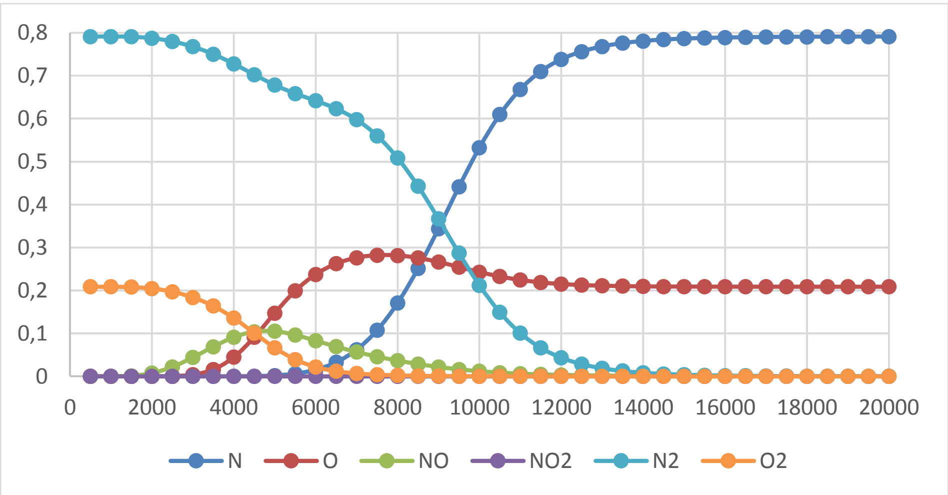

Figure 3: Equilibrium mole fractions of chemical components of dissociating N2-O2 plasma in temperature range up to 20000 K for applied reaction mechanism

DOI: 10.13009/EUCASS2017-371

This is known [1] that flow coming after arc-heated high-enthalpy generator has parabolic temperature profile. As an inlet boundary condition, parabolic temperature profile was introduced, with mean gas temperature in order of 6000…7000 K. Dissociated N component fraction at the inlet was varied depending on temperature according to equilibrium value calculated in CHEMKIN.

3. Simulation results for simplified geometry

Simplified geometrical model is shown on Figure 4. Two geometries were considered – with one orifice for transverse injection, and with series of 8 orifices placed in one section. Main duct diameter is equal to 20mm and orifices diameter is 4mm.

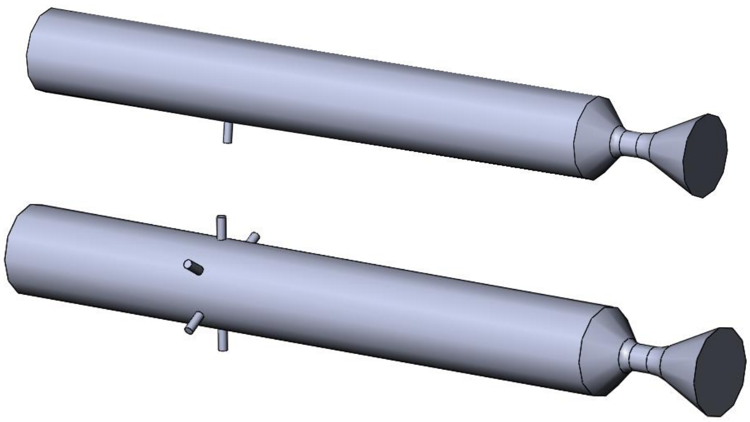

Figure 4: Geometrical configurations considered for preliminary modelling stage. a) – one orifice for cold oxygen injection; b) – 8 cold oxygen injection orifices placed in one section

Computational mesh (Figure 5) was generated using CutCell method. Mesh resolution is refined in a region of injection and excessive chemical reaction area. Mesh for simplified geometrical models has around 4 million elements.

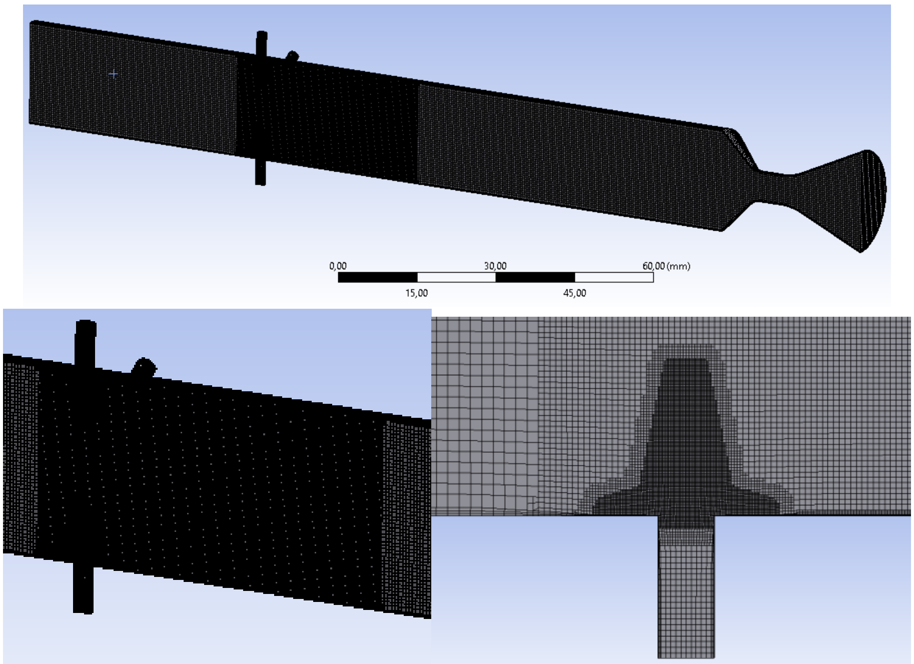

Figure 5: Computational mesh

Instantaneous temperature and species fractions in symmetry plane and at the outlet are presented on Figures 6 and 8, and time-averaged contours of temperature and species fractions are presented on Figures 7 and 9. Operational parameters are given in captions.

DOI: 10.13009/EUCASS2017-371

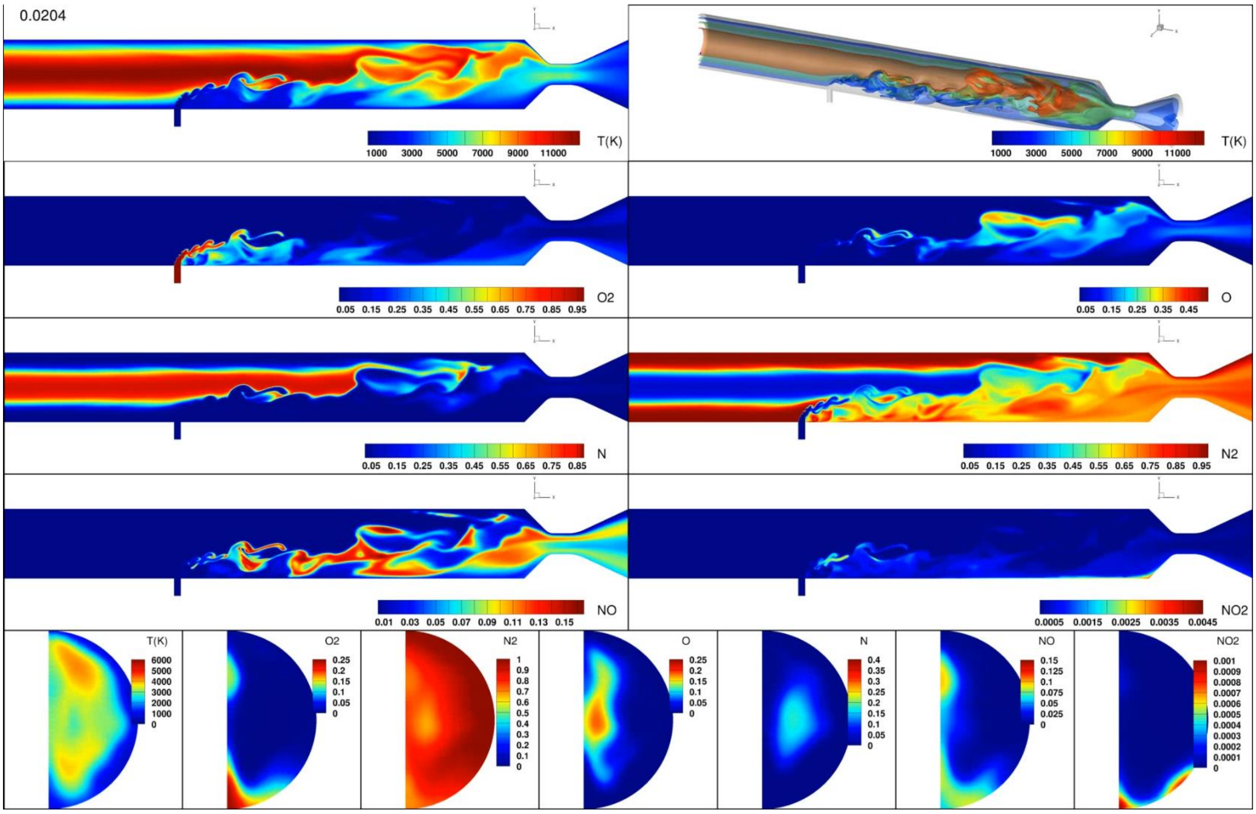

Figure 6: Instantaneous contours of static temperature and chemical components fractions in the symmetry plane and at the outlet for configuration with one orifice cold injection. $\overline{T_{in}} = 6000\ K,\ \ m_{in\ hot}^{\cdot} = 30\ g/s, m_{in\ cold}^{\cdot} = 20\ g/s$

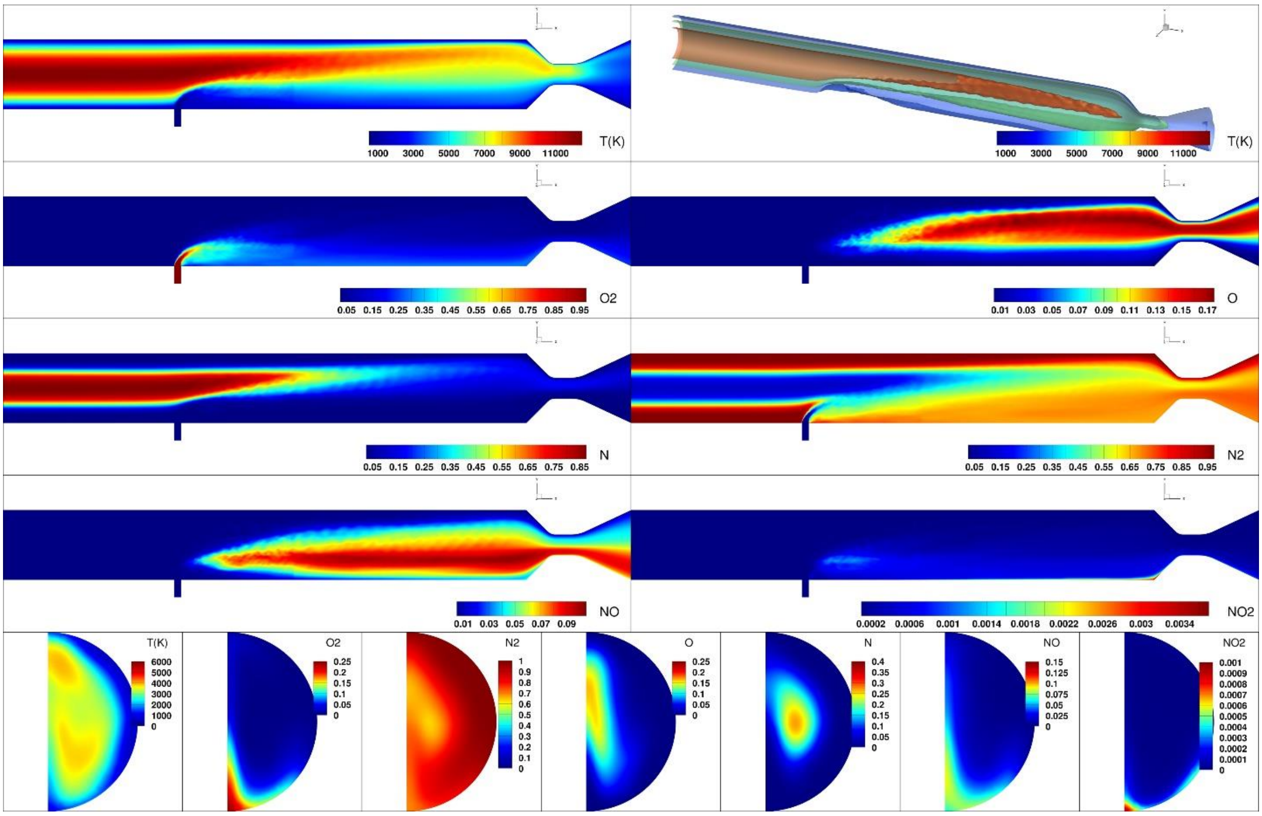

Figure 7: Averaged contours of static temperature and chemical components fractions in the symmetry plane and at the outlet for configuration with one orifice cold injection. $\overline{T_{in}} = 6000\ K,\ m_{in\ hot}^{\cdot} = 30\ g/s,\ m_{in\ cold}^{\cdot} = 20\ g/s$

DOI: 10.13009/EUCASS2017-371

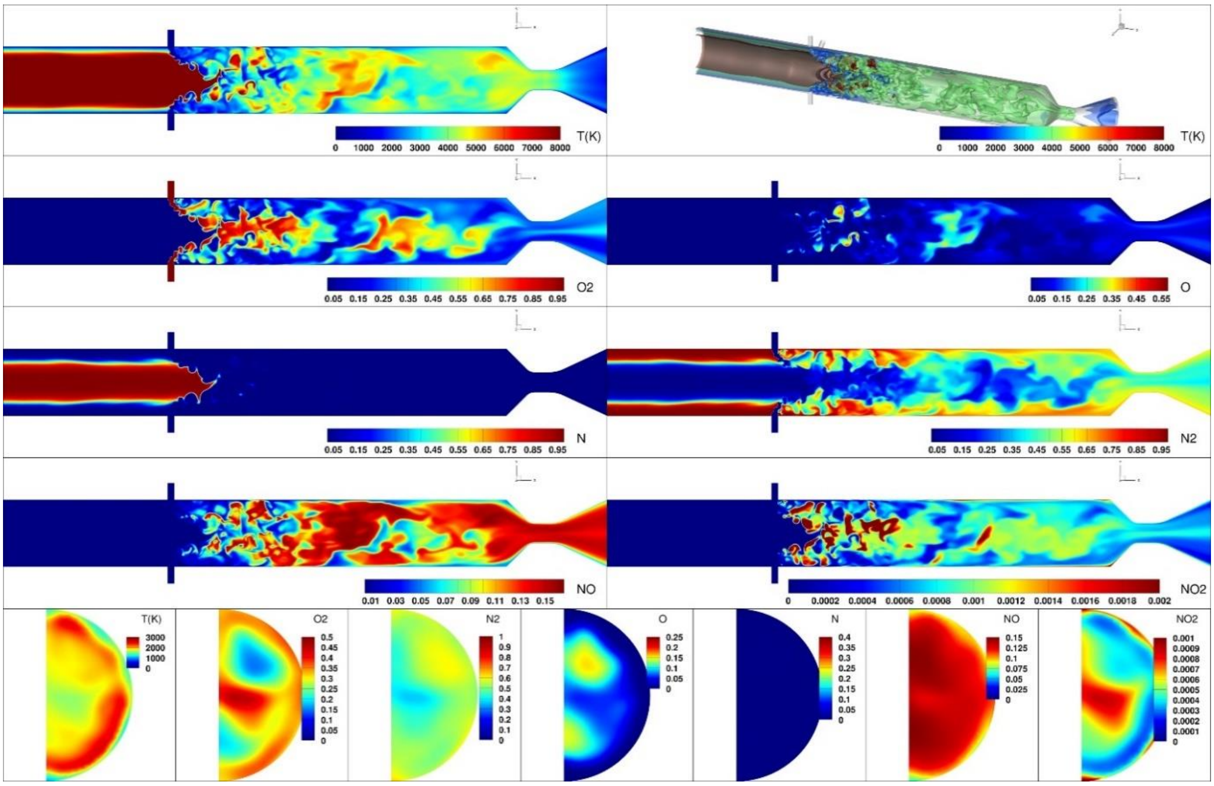

Figure 8: Instantaneous contours of static temperature and chemical components fraction in the symmetry plane and at the nozzle outlet for configuration with 8 cold oxygen injection orifices placed in one cross section. $\overline{T_{in}} = 7000\ K$, $\dot{m_{in}}_{hot} = 30\ g/s,\ \dot{m_{in}}_{cold} = 20\ g/s$

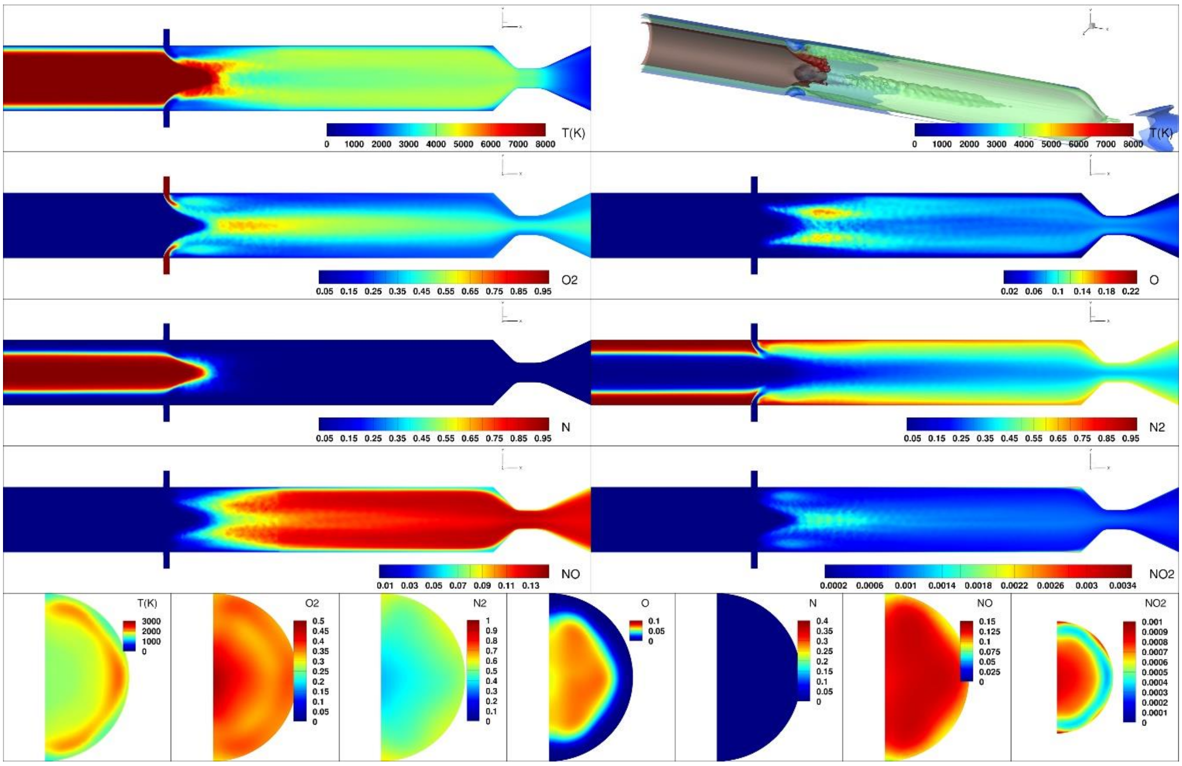

Figure 9: Averaged contours of static temperature and chemical components fractions in the symmetry plane and at the nozzle outlet for configuration with 8 cold oxygen injection orifices placed in one cross section. $\overline{T_{in}} = 7000\ K$, $\dot{m_{in}}_{hot} = 30\ g/s,\ \dot{m_{in}}_{cold} = 20\ g/s$

DOI: 10.13009/EUCASS2017-371

Analyzing temperature and species contours plots it may be concluded that with one transverse injection it is very difficult to obtain smooth outflow profile. Although cold jet nearly reaches duct centerline, many unaffected areas still remains at the top and at the sides of the duct. Consequently, mixing is mainly occurring at the bottom side of the duct.

Example with 8 orifices in one cross section gives much better results for mixing efficiency. Although, for the case considered, cold jet momentum appears too strong, what results in center having lower temperature then periphery, as shown on Figure 9. Portions of high-enthalpy gas splits and squeeze between strong cold jets towards periphery. O2 also tends to concentrate near centerline and doesn't distributed evenly at the outlet.

For both cases instantaneous contours differs considerably from average, what is the nature of turbulent mixing. Physical time calculated is around 0.01 s, while time step applied during simulation is 5×10^{-7} s. During operation, high-enthalpy gas may follow through the duct in portions, resulting in time-varying temperature peaks on the outlet. For the T-shape mixing chamber it will be desired to dissipate high-enthalpy peaks in order to reduce impact on experiment quality.

Considerable amount of NO is observed for both cases, what is corresponds to equilibrium calculation range for temperatures 3000…4000 K. In current calculation up to 15% mass fraction of NO is produced.

4. Simulation results for T-shape chamber

Segmented cold injection section and final T-shape configuration was analyzed using simplified model without chemical reactions for the purpose of lowering computational efforts. Computational mesh for current cases is around 20…40 million elements, so considerable computational resource required to achieve solution. Only O2 and N2 species considered on the current development stage. Instantaneous temperature contours for segmented injection section are presented on Figure 10.

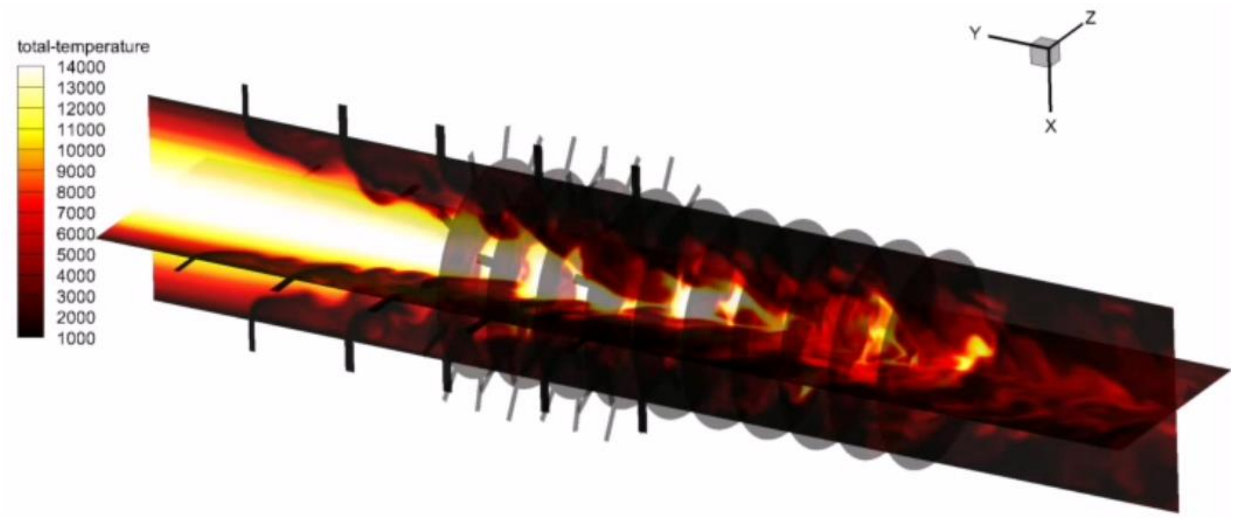

Figure 10: Instantaneous contours of static temperature in the symmetry planes and cross-sections for one full cold injection module section geometry. $\overline{T_{in}} = 7000\ K,\ \dot{m_{in}}_{hot} = 1\ kg/s,\ \dot{m_{in}}_{cold} = 1{,}2\ kg/s$

In that case series of injection collectors were introduced. 8 collectors with 12 orifices each are combined in the injection section. That configuration will allow for multiple operation regimes calibration. On the current simulation case presented results with cold jets having little strength, so centreline remains slightly overheated.

Figure 11 represents final model T-shape mixing chamber simulation results. Presented operation regime also has weak cold jets. As a result, oxygen tends to concentrate near periphery and centerline flow remains overheated. In place of T-joint, two overheated main flows impact each other, forming time-varying high-enthalpy areas transferring through the fine mixing duct towards the throat nozzle section. The regime presented is undesirable and should be avoided by redistributing cold gas in the cold injection sections.

During further research, other operating cases will be considered so that uniform temperature distribution and species fraction profile at the outlet is achieved.

DOI: 10.13009/EUCASS2017-371

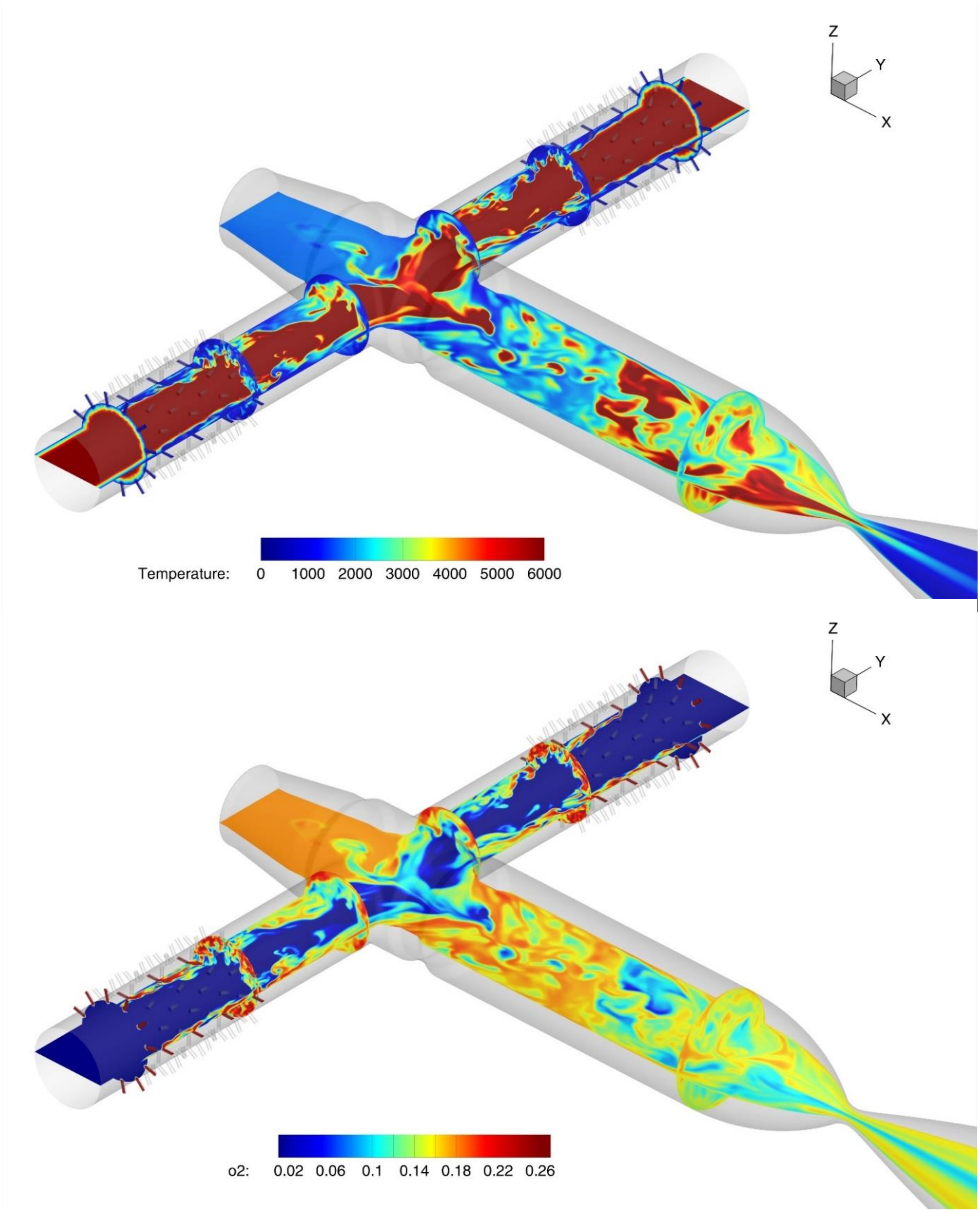

Figure 11: Instantaneous contours of static temperature and O2 mass fraction for T-shape mixing chamber model calculations. $\overline{T_{in}} = 7000\ K$, $\dot{m_{in}}_{hot} = 2\ kg/s$, $\dot{m_{in}}_{cold} = 2{,}5\ kg/s$. Insufficient mixing quality observed for current case.

DOI: 10.13009/EUCASS2017-371

5. Conclusion

The step-by-step study of T-shape mixing chamber by numerical simulations technique is described in this paper. Hybrid RANS-LES model allows for detailed examination of flow patterns and mixing quality, taking into account turbulence and chemical reactions. This is shown that with transverse cold gas injection through series of distributed orifices this is possible to obtain qualitative mixing and enthalpy reduction from initial 10…20 MJ/kg down to 3…5 MJ/kg for considered chamber.

As a further research steps, different operation regimes for injection section and T-shape geometry will be considered. In addition, more complicated chemistry model may be tested and validated. Experimental results are required to prove theoretical model and may be achieved on mixing chamber operation stage.

References

[1] Koroteev A.S., Mironov V.M., Svirchuk Y.S. 1993. Плазмотроны. Конструкции, характеристики, расчет. Москва, Машиностроение.
[2] Antonio Del Vecchio. Federico De Filippis. 2003. SCIROCCO Plasma Wind Tunnel: Enthalpy Lowering by Use of Cold Air Transverse Injection. AIAA 2003-6959.
[3] Schetz J.A. 1980. Injection and Mixing in Turbulent Flow. Progress in Astronautics and Aeronautics, Vol. 68, 145-164.
[4] D.M. Smith and E.J. Felderman. 2006. Aerothermal testing of Space and Missile Materials in the Arnold Engineering Development Center Arc Jet Facilities.
[5] Jachimovski C.J. 1998. An analytical study of the hydrogen-air mechanism with application to scramjet combustion. NASA-TP-2791 Report.
[6] Alexander Burcat, Branko Ruscic. 2005. Third Millenium Ideal Gas and Condensed Phase Thermochemical database for Combustion with Updates from Active Thermochemical Tables.