ESTIMATION OF BOUYANCY EFFECT AND PENETRATION LENGTH OF JET FROM AIRCRAFT ENGINE BY LES METHOD

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SUMMARY

Numerical simulations of exhaust gases jet was implemented on the basis of 3D model of Fluent 6.3 by using Large Eddy Simulation method, which allows investigating unsteady nature of the ground vortex and turbulence characteristics of fluid flow, estimating transient parameters of hot gases jet and its dispersion.

Keywords: exhaust gases jet, aircraft engine emission, buoyancy effect, jet penetration

INTRODUCTION

Air pollution resulting from airport emission sources is a growing concern because of continuous air traffic growth and appropriate airport expansion over the years. Future air traffic is forecasted to grow at a mean annual rate of about 5 % worldwide [Graham et al., 2003], thus fuel consumption and aircraft engine emission will rise accordingly as at local, so as at global levels of air transportation.

During last decade there were many studies focused on impact of aircraft engine emissions on local air quality (LAQ) including results of their modelling and direct measurements in vicinity of the airports [Celikel et al., 2005; Schäfer et al., 2003; Schürmann et al., 2007]. LAQ is an actual problem for city airports and for airports, which are quite closely located to habitation areas, so the impact of aircraft engine emission on urban air quality is high, somewhere it is over the standard limits for appropriate contaminations. Currently the basic matters of close attention are the gaseous nitrogen oxides (NO_x) and particle matter (PM) from aircraft engine emissions, because they are initiators of photochemical smog and regional haze, which may further impact on human health directly.

Aircraft in operation (during approach, landing, taxiing, take-off and initial climb – landing-takeoff cycle or LTO-cycle) and maintenance (aircraft engine run-ups) is a dominant source of LAQ in vicinity of the airport in most cases under consideration.

Air pollution from aircraft engine emissions and engine jet behavior depend both on: number of engines, engine nozzle parameters and height of its installation, distance between engine nozzle centerlines, and where engines are mounted – on fuselage or on wing of the aircraft. To assess their contribution in LAQ assessment it is important to take in mind few features, which define emission and dispersion parameters of the source.

First important feature of the source of emission under consideration is a presence of a jet at engine exhaust nozzle, which contains significant momentum and thermal buoyancy and in accordance may transport contaminant on rather large distances and the rise the plume centerline over the height of engine installation and over the ground surface appropriately. The value of such a distance is defined by engine power setting and installation parameters, mode of an airplane movement, meteorological parameters. The results of the jet model calculations, depending on listed initial data, show that the extent of transport of the jet plumes from aircraft engines may change within the 20...1000 m and sometimes even more [Zaporozhets et al., 2005].

Second, aircraft is a moving source with spatially and temporally changing of velocity, acceleration and direction of the aircraft movement within wide limits inside the territory of LAQ assessment.

During take-off and landing the wings of an aeroplane produce lift which in turn generates powerful trailing vortices. The engine jets are entrained into the two counter-rotating wingtip vortices, at specific (and over them) aeroplane velocities the jet efflux rapidly mix with ambient air while the vorticity shed from wings rolls up into a pair of trailing vortices [Labbé O., 2006].

Until today, current models EDMS [FAA-AEE-01-01, 2002], LASPORT [Janicke U., 2005], PolEmiCa [Zaporozhets et al., 2005] use semi-empirical approaches for description of fluid dynamic of jet plumes from aircraft engine and do not take into account an influence of the ground on jet behaviour and on its vortical structure. Eliminating the fluid mechanisms in considered modelling systems may overestimate the height of buoyancy exhaust gases jet from aircraft engine, underestimate its length and radius of expansion, dispersion characteristics and contaminants concentration values.

The work presented here was aimed to improve complex model PolEmiCa by using CFD tool Fluent (version 6.3) for simulation of the aircraft engine jets near the ground surface. Numerical investigation of properties and structure of aircraft engine jets allow to get a deep understanding of the fluid mechanics, the jet dynamics and transport process of contaminates and their dilution by jet near the ground. Taking into account the impact of ground surface on jet structure and its behavior (Coanda and buoyancy effect) may provide more accurate results for estimation of basic parameters of the jets (height and longitudinal coordinate of jet axis rise due to buoyancy effect, length of jet penetration and dispersion (deviation) characteristics).

So, results of this investigation allow implementing accurate simulation of aircraft engine jet in dispersion modeling systems and accurate assessment of aircraft emission contribution to total air pollution at the airport.

Complex model PolEmiCa

A complex model PolEmiCa (Pollution and Emission Calculation) for assessment of air pollution and emission inventory analysis, produced inside the airport, has been developed in National Aviation University (Kyiv, Ukraine) In National Aviation University (Kyiv, Ukraine) [Zaporozhets et al., 2005]. It consists of the following basic components:

1. **engine emission model** – emission factor assessment for aircraft engines, including influence operation factors;
2. **jet transport model** – transportation of the contaminants by jet from aircraft engine exhaust;
3. **dispersion model** – dispersion of the contaminants in atmosphere due to turbulent diffusion and wind transfer.

In the scope of this paper **the jet transport model** will be represented, which evaluates basic mechanisms of contaminants transportation and dilution by exhaust gases jet from aircraft engine and provides basic parameters of jet, as initial data – height and longitudinal coordinate of buoyancy effect, length of jet penetration and dispersion characteristics – to the dispersion model, fig. 1.

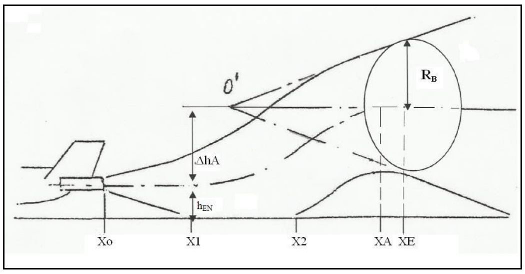


Fig. 1. Jet structure for jet transport model: Δh_A, X_A – height and longitudinal coordinate of jet axis rise due to buoyancy effect, m; h_{EN} – height of engine installation, m; R_B – radius of jet expansion, m; X_1 – longitudinal coordinate of first contact point of jet with ground, m; X_2 – longitudinal coordinate of a point of jet lift-off from the ground due to buoyancy effect, m.

The process of contaminant transport by exhaust gases jet is described by the theory of turbulent jets [Abramovich G., 1960]. The restriction on use of the given theory satisfies to conditions of a considered task [Tokarev et al., 1987]: the gas flow in jet is isobaric process. The Mach number of jets at section of outlet nozzle of the engine does not exceed 1. The pressure of fluid flow jet is equal to the atmospheric pressure, which is corresponding to the nature of incompressible flow. Reynolds number for a flow rather large ($U_0 d_0/\nu > 10^4$), initial turbulence in jet flow is moderate. In the majority of the calculation algorithm cases it was used the simplifying preconditions: radial profile of velocity has a self-preserving pattern; mechanisms of boundary layer formation near restricted surface (ground) are not taken into account in calculation; the external borders of a flow represent linear dependences; similarity structure of shear layer with free jet. Last assumption is agreed with the comparison of Fortmann's experimental data for the wall jet [Forthmann E., 1936] and the theoretical results of Tollmien, Goertler and Bradbury for the free jet [Gebhart et al., 1988; Bradbury et al., 1965].

As follows from the analysis of measurements' results, the buoyancy effect of exhaust gases jet is observing over boundary surface [FAA, 20501, 1977; Smith et al., 1977]. Buoyancy of a jet is caused by action of Archimedes forces due to excess of temperature of jet gases above air temperature, fig.1.

For an estimation of the buoyancy characteristics the Archimedes number:

$$Ar_0 = {g \times D_0 \times (Q_T - 1)} \big/ {U_0^2}$$

is used which can be performed as a function of engine power setting [Zaporozhets O., 1986], see fig. 2. Parameter $Q_T = T_0/T_H$ for a modern engines changes within the limits of 1.15... 2. The height of plume rise is defined by empirical formula [Zaporozhets et al., 2005]:

$$\Delta h_A = 0.013 \times Ar_0 \times X_A^3 \times R_0$$

where X_A is the longitudinal coordinate of jet axis

Complex model "PolEmiCa" is based on semi-empirical model of turbulent jets and not taking into account ground impact on jet structure and its behaviour. It was argued [Chan et al., 2005], that intensity of the ground vortices is much stronger than ones created by the surrounding fluid and define tendency of jet flow development. So, development of three-dimensional model of exhaust gases jet from aircraft engine near ground is an actual research topic for airport local air quality.

LARGE EDDY SIMULATION OF EXHAUST GASES JET FROM AIRCRAFT ENGINE NEAR GROUND

Numerical simulation of wall jet was performed with CFD package (Fluent 6.3), which is corresponding to model of exhaust gases jet from aircraft engine near ground. Nozzle diameter of aircraft engine exhaust, D is 1.0 m, the height of engine installation, h_{en} above the ground – 3.5 m.

This investigation was aimed for improvement of complex model PolEmiCa to obtain solutions of the following tasks:

- understanding of aspects of the fluid mechanics and emission source dynamics behind an aircraft engine;
- investigation of the physics and characteristics of ground vortices, which are generated between the ground and the aircraft engine nozzle, up to the moment of transport of the air pollution by wind;

• assessment of the ground surface impact on the flow structure, parameters and basic mechanisms of jet.

For these tasks a three-dimensional model of a jet was generated in Fluent on the basis of involving the computational grid, which is represented by a combination of cylindrical and parallelepiped regions. This computational domain is characterized by highest resolution with number of computational cells equal to 1376100.

Three-dimensional flow field and unsteady nature of the ground vortices determine complication of features and behavior of the aircraft engine exhaust jet. For expressed reasons, Large Eddy Simulation (LES) method was used to reveal the unsteady ground vortices and turbulence characteristics of fluid flow, investigate transient parameters of hot gases in jet and their dispersion. LES provides an approach inside which large eddies are explicitly resolved in time-dependent simulation using low-pass filtered Navier-Stokes equations. The smaller eddies are modeled through a filtering process due to their universality and their lesser influence on the fluid flow. Smagorinsky's sub-grid model was set to model the smaller eddies (fluctuation component of instantaneous velocity of modeling fluid flow) that are not resolved in the LES. The employed computational mesh satisfies to requirements of LES application – high density and structureness – to capture eddies of acceptable size. For considered task the following boundary conditions were specified to the boundaries of the computational domain of jet flow field, fig. 2:

• The nozzle section of aircraft engine exhaust at which jet hot gases enter to computational domain is set as a "velocity inlet**"**;

• The computational surfaces adjacent to the engine section at which ambient conditions (wind velocity, wind direction and temperature) enter to computational domain is also set as "velocity inlet";

• The external lateral surfaces of computational domain at which ambient conditions (wind velocity, wind direction and temperature) are set as "velocity inlet**"** also: wind direction and velocity were defined by velocity specification method, X-component of flow direction = 1;

• The ground surface, which is corresponding to the bottom of the computational domain, is set as "wall" implying a non-slip condition for velocity and with temperature 300 K. To evaluate the phenomenon of ground vortices formation between the aircraft engine exhaust and restricted surface the boundary conditions on ground surface cannot be considered anymore as a "wall**".**

• The computational surface opposite to the aircraft engine exhaust nozzle, at which flow field (mixture jet and ambient air) leaves computational volume, was set as "pressure-outlet".

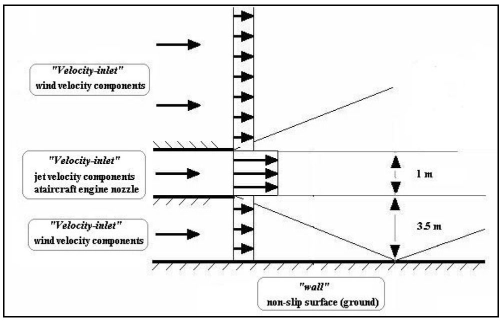


Fig.2. Boundary conditions for Fluent 6.3 simulations of exhaust jet from aircraft engine near ground

All the calculations were made with a second order discretization.

MODELING RESULTS COMPARISON

Modeling of exhaust gases jet from aircraft engine for different operational conditions was implemented on the basis of complex model PolEmiCa (free jet) and three-dimensional model (wall jet) using Fluent (version 6.3), LES method.

So, for initial velocity 50 m/s, calculated length of jet penetration by Fluent 6.3 exceeds the averaged value on 5% by complex model PolEmiCa (fig.3, 4). And longitudinal coordinate of buoyancy effect calculated by Fluent 6.3 is longer on 30% while the height of jet rise is lower on 24 % in comparison with complex model PolEmiCa. Obtained difference of basic jet parameters is explained by ignoring the impact of restrictive processes on the surface topology and properties of the jet in complex model PolEmiCa.

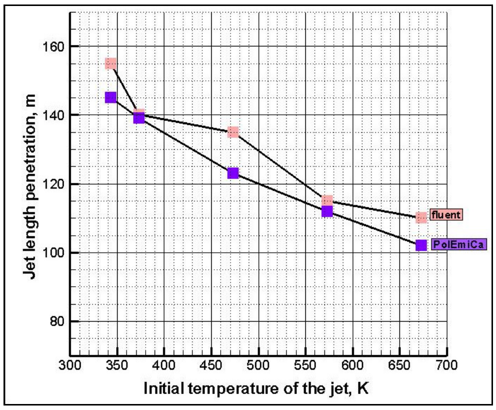
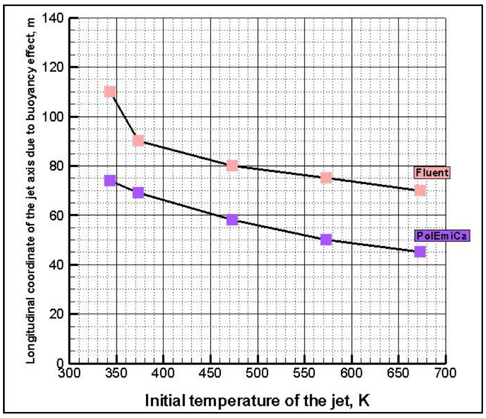
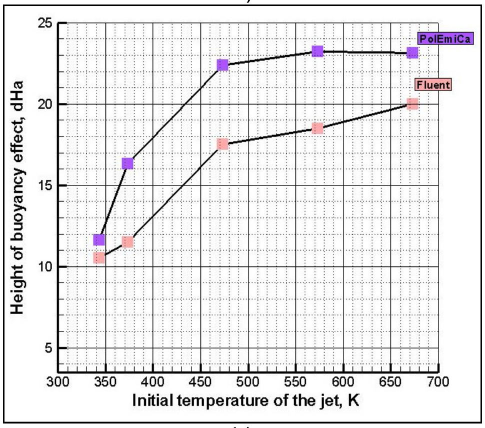


Fig. 3. Comparison of jet penetration length calculated by Fluent 6.3 and complex model PolEmiCa



a)

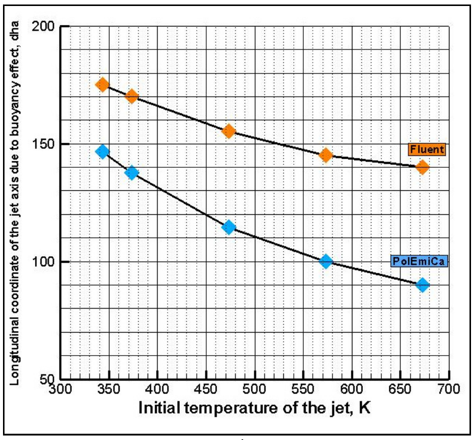


b)

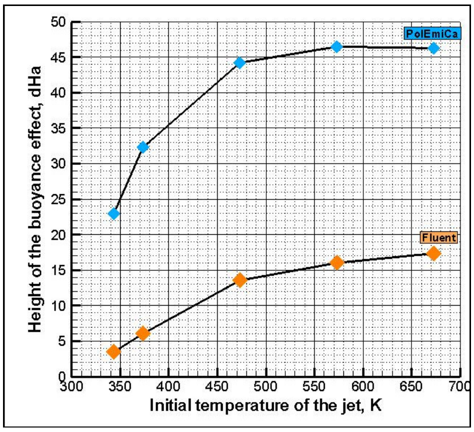
Fig.4. Comparison of buoyancy effect parameters calculated by Fluent 6.3 and complex model PolEmiCa: longitudinal coordinate (a) and height of jet rise (b)

For, initial velocity 100 m/s, ground sufficiently impacts on jet's structure and behavior.

So, numerical simulations of wall jet by Fluent 6.3 have highlighted on decrease of buoyancy effect height in 3-5 times and on increase of longitudinal coordinate of jet rise on 30%, fig.5.



a)



b)

Fig.5. Comparison of buoyancy effect parameters calculated by Fluent 6.3 and complex model PolEmiCa: longitudinal coordinate (a) and height of jet rise (b)

Comparison of obtained results of numerical simulations of Fluent 6.3 and jet semi-empirical model (PolEmiCa) allow revealing impact initial conditions on jet structure and properties.

CONCLUSIONS:

On the ground of numerical simulations for wall jet was found that jet structure and its behavior depends on the velocity ratio U_{jet}/U_{wind}. Since higher initial velocity of jet and lower height of engine installation lead to push down and clinging of the flow o the ground, also known as the Coanda effect. The increase of longitudinal coordinate and decrease of height of buoyancy effect caused by high intensity and scale of ground vortices and their impact on jets parameters. While lower initial velocity of jet and higher height of engine installation lead to lift and rise of the flow above the ground, also known as buoyancy effect. So, Fluent 6.3 allow improving complex model PolEmiCa by taking into account ground impact on structure and behavior of gases jet from aircraft engine exhaust. CFD codes allow solving quite complex equations to obtain detailed results of high quality material, on the base of which a necessary scientific reasoning of transportation of the contaminants by aircraft engine jets, ground impact on dynamic and topology of fluid flow jet should be used for improving of methods for assessment of aircraft emission contribution to total air pollution inside the airport.

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