The analysis of a reverse jet influence on flow parameters at engine inlet and particles ingestion

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Abstract

Reverse mode of a operating near ground jet engine was considered. Calculation of air flow and particles trajectories under the engine intake was performed. At the base of numerical and theoretical analysis of air flow and particles trajectories some conclusions about probability decreasing of big particles transportation to engine were performed

Introduction

Low underwing engine location which is typical for modern civil airplane configurations is causes of a number of unfavorable factors and increasing probability of transportation to engine inlet of big particles is one of them. Among reasons for big particles scattering and suction in engine are landing gear motion on the ground, an action of a reverse jet and powerful vortex flow which realized under engine operation near surface.
Regime of trust reversing which used for airplane braking on the ground is one of critical regimes for safety and reliability of aviation engines. During the thrust reverse activities the probability of big particles suction into engine which leads to blade damage is sufficiently increase. Additionally the suction of exhaust gas to the engine begins possible that leads to increased nonuniformity of flow parameters.
The particle motion can be caused by some kind of mechanical action ore by vortex flow and reverse jet action on the near surface engine operation regime. It is necessary to distinguish these reasons.
The vortex flow has a property of particles accumulation in the near to surface region of its influence. As a result the flow lifts particles from this region to the engine inlet. Sizes of lifted by vortex flow particles depends from a rotation motion intensity. Particles lifting process is very difficult and depends from a number of different effects: particles shifting and transporting by flow, interaction between particles and so on. In [1,2] was shown that size of lifted by vortex flow particles can be in ten times more than that without vortex.
In the interaction of a reverse jet and a counter flow also arise conditions for particles accumulation in a zone of a flow turn. In accordance with [1,2] this leads to conditions for big particles suction arising. The analysis of the interaction of reverse jets which extend along the surface and turned by the counter flow with a flow at the engine input is demonstrate that conditions for big particles suction into the engine are significantly increased.

1. Particles accumulation in a vortex

Detailed analysis of a process of particles accumulation in a vortex was performed in [1,2]. Therefore in this section only main results of that which are important for the problems of reverse jet influence to the big particles suction to engine inlet will be considered.
For particles lifting by flow is needs that drag force f was grater then gravity force P. For evaluation of a lifted particles maximum diameter from the equilibrium conditions $P=f$ can be deduced

$$d=\frac{3\rho}{4\rho_P g}\cdot u^2$$

where u is a flow velocities, ρ_p – particle densities, ρ - density of moving environment (it is accepted that Stoks factor of resistance is $C_x = 1$).
For the further analysis of a velocities component distributions it is convenient to use the speed U which is induced in the near surface layer by the intake duct with radius R_i. In the free space the velocities level of speed on the distance H from the intake channel can be estimated by means of a equation

$$U/u_i = (1/2 \div 1/4) \quad R_i^2/H^2 \quad ,$$

Coefficient ½ is correspond to a small values of ratio H/R_i, coefficient ¼ is correspond to $H/R_i \to \infty$. Here u_i is a velocity of inlet flow in the duct and R_i it's radius. In the case when at the distance H surface is located the values U can be used for evaluation of the induced near surface velocity.
Numerical analysis of realized in the near surface region flow under operation engine [1-3] is demonstrates that in this region velocities is not bigger than induced velocity U. The values of vertical velocity increase from zero and achieve a value $V_z \approx U$ at the height approximately R_i above the surface. Therefore the air motion in the near surface region cannot move big particles. The small particles accumulation in the vortex region is need for a big particles lifting. This creates a moved medium which medium densitiy ρ is sufficiently greater than that in the air. Accumulation time was evaluated at [1] and for real conditions is approximately some seconds. Small particles create the vortex visualization effects that demonstrate by figure 1.

Figure 1: Photo of vortex flow at the engine inlet.

At airplane movement the vortex flow on an engine input does not disappear and moves with it. It is confirmed by the correspondent numerical calculations. But conditions for particles accumulation at the vortex basis are disturbed and an illusion of a vortex disappearance on an engine input at airplane movement with velocities greater then several meters per second is arrive. In [1-3] numerical calculations of flow was performed which are demonstrated that for real airplane engine configuration at velocity of a counter flow 50 m/s the intensity of vortex flow decreases only for some percent. It shows that the vortex flow at engine inlet exists in all modes of movement in airplane landing.

2. Reverse jet propagation

2.1. Problem formulation

In the scope of this section the jet propagation from the thrust reversing device along a surface and its hit to air intake are considered. Therefore aspects which are connected with features of jet creation, leakages and construction of thrust reverse device was not considered. The model of pod for engine with bypath ratio approximately 10 was used for calculations. (figure 2,a,b).
Experience of the model thrust reverse devices numerical simulations was demonstrate that detailed geometry of devices has a influence to the flow parameters inside them and to the characteristics of initial part of reversing jet. But jet propagation in the flow is practically independent from this geometry and depends only from angle of exit flow and its total parameters. Therefore for saving of numerical resources instead the detail description of the thrust reverse devices the cavity in the pod surface was used. The spatial orientation of cavity was corresponding to orientation of the initial part of reverse jet and its size was corresponding to size of reverse door or cascade. At the cavity bottom the total parameters of jet was set. Loses inside the thrust reverse device was not considered in this work. Therefore total parameters of reverse jet were corresponding to total parameters in engine secondary flow. This approaches is not give the opportunity to investigate the problem of jet adhering to pod, effectives of selected thrust reverse device and so on. But such approach is applicable for reverse jet propagation descriptions.
Inside the air inlet in the cross section which is corresponding to fan inlet plane the static pressure was set. Value of that was selected from the condition of prescribed mass flow rates throw air inlet.
In the table the flow parameters are described.

Table 1: Engine operation parameters

G_2, kg/s	P_2*, kg/cm^2	T_2*, K	G_1, kg/s	P_1*, kg/cm^2	T_1*, K
400	1,5	320	40	1,1	800

a

b

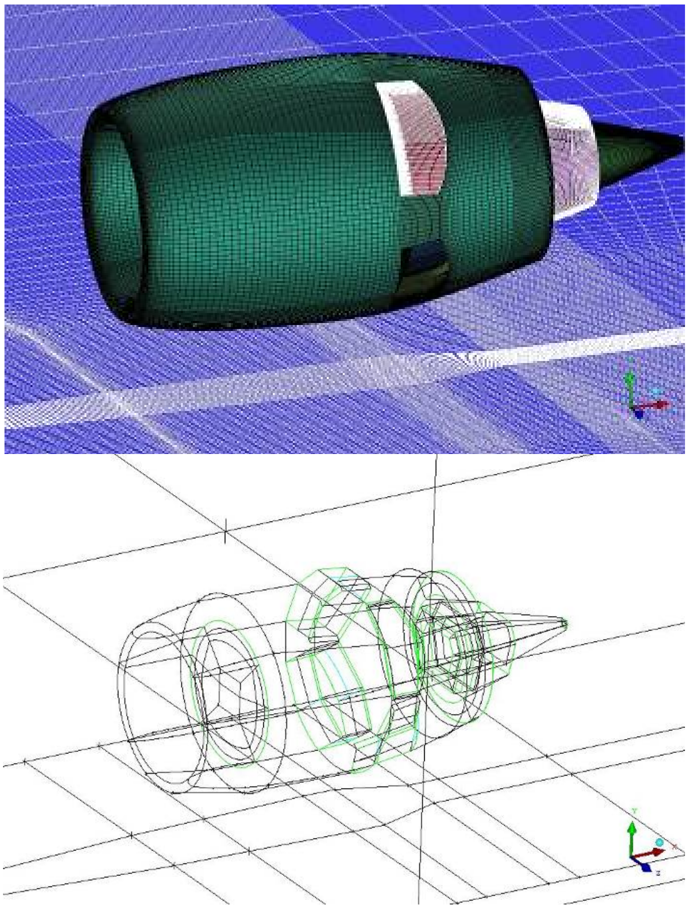


Figure 2: (a) – external view of pod and model of thrust reverse device;
(b) – topology of calculated area on the pod and ground surfaces

Here *G* is a mass flow rate, *P** and *T** is a total pressure and temperature. Subscript «1» is corresponding to the primary flow parameters and «2» -to the secondary flow parameters. Mass flow rate thru air intake was set as a sum $G_1 + G_2$.

Into the [1,2] was demonstrate that exhaust jet have a influence to parameters of flow before air intake. Therefore the used model was including the path of the nozzle for exhaust jet modeling for this effect allowing. Exhaust jet flow parameters was setting in accordance with primary flow parameters.

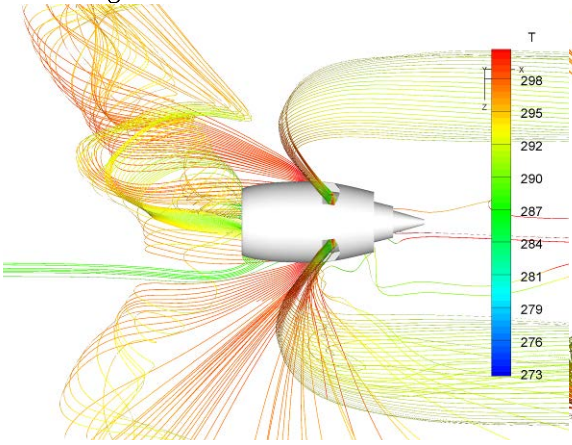
Sizes of the calculated zone were selected for excluding of boundary influence to the flow near engine. Distances between pod and front and side boundaries were 30 inlet diameters and between pod and back side was 50 inlet diameters. Distance between engine and down side is corresponding to height of engine location.

Home made in CIAM CFD solver Cobra was used. This program was developed for the solution of aerodynamic problems at the base of RANS technology (at the base of numerical integration of Reynolds equation closed by turbulence model ν_t-90). This program is using multibloc mesh. In the fig.2,b the topology of mesh which was used for calculations is demonstrated. This mesh is thickened to the pod and ground surfaces. The calculated with the size of the first near surface cell value of y^+ was equal to 10 for pod and 1 for ground. For significant decreasing of cell numbers the pod surface was surrounded by "O-grid". In this case the scope of thickened sell is located only around the pod and not propagates far from that. Total block numbers of developed mesh was 340.

For enlarging of the spatial resolution in the region of reverse jets propagations the nested grid was used. In the some mesh blocks which located between pod and ground and before ground the number of cell in all directions was timed to two. Total cell number was more than 6 millions. And 3 millions were located in the down surrounds of engine.

2.2. The calculations results

For fixed geometry of calculation region (figure 2,a) and operation parameters of engine (table) the number of calculations was performed for different airplane velocities.
It was shown that the location of points where flow lines is reversed is create the pronounced boundary (figure 3) that have a U-form near the engine symmetry plane. This fact is in a good agreement with experimental data [3]. In the case when the airplane velocity u_∞ is approximately 50 m/s the distance between engine inlet and front of flow line reversal in the direction of engine axis is near to one diameter. When the $u_\infty \approx 30$ m/s then this distance became twice (figure 4). Colors in these pictures are demonstrating the static temperature distribution along flow lines and in the section of engine inlet.



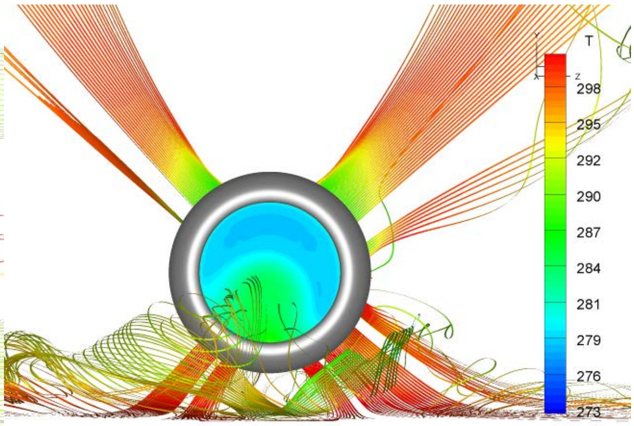


Figure 3: Flow lines at u_∞= 30 m/s.

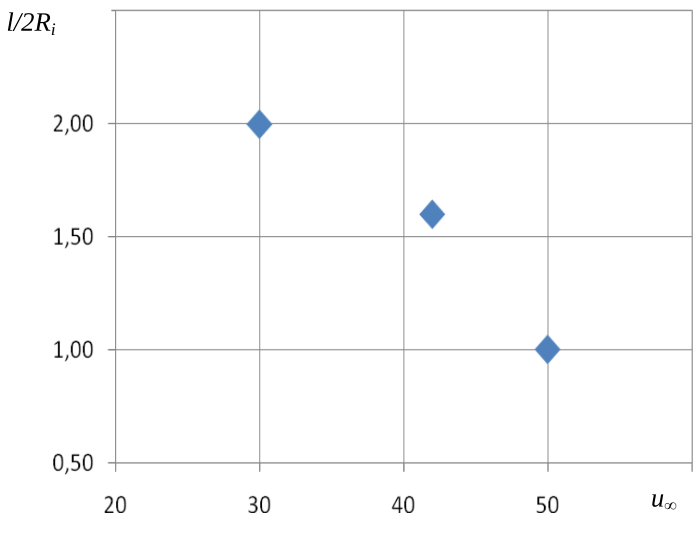


Figure 4: The dependencies of distance between engine inlet and reverse jet reversing point l from airplane velocities. R_i is a engine inlet radius.

2.3. Additional effects which leads to increasing particles ingestion probability

The reverse jet during its propagation along a surface has a permanently decreasing axial velocity component. In some moment this component gets over zero and changes its sign. As was illustrated above the region of reversed jet reversing create the uninterruptible boundary which is moved together with airplane. The high-pressure reversed jet is initiating the motion of located on surface large enough particles when it is striking into a surface. Near the symmetry plane the axial velocity component is achieve the 90% of absolute velocity. In the region of reversed jet reversing this component became zero and moved particles which were seized by the jet are return to surface again. This leads to creation of a zone with increases particles concentration. Permanent accumulation of particles inside this zone will be take place during the airplane motion along surface. Such accumulation inside zone which is moved before airplane is similar to bulldozer effect.

It must be noted that during the one cycle of the reversed device operation the zone of increased particles concentration pass twice near the air intake. In the moment of reverser activation the first time and after it's deactivation the second time. First pass is not such dangerous because reversed jets haven't time to accumulate the large number of particles. In the second pass the existing on the air intake vortex appeared in the conditions when the particles concentration is sufficiently large than in the other places on the surface. This leads to a decreasing to practically zero the particles accumulation time which is need for creation of conditions for big particles ingestion into the air intake.

The scheme of reverse jet propagation near surface is illustrated in the figure 5. The main part of jet flow is propagate in the airplane direction of motion. That is jet propagates in a counter directed air flow which at some distance form jet source (or from the region of jet strike to surface) decelerate and reverse it. Under uniform airplane motion and stationary jet outflow the distance from jet source to reversing zone will be constant.

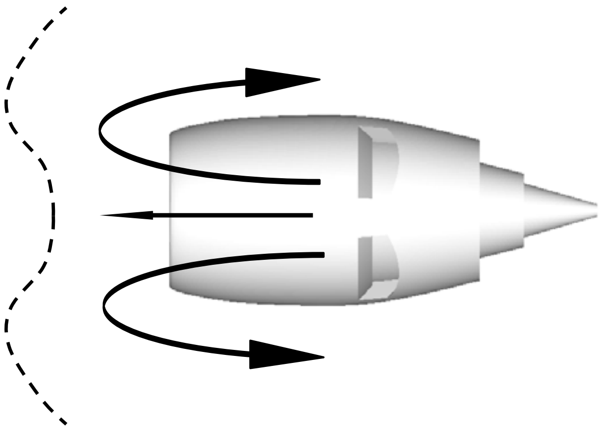


Figure 5: Scheme of reverse jets propagation. Solid line is a reverse flow and dashed line is a jet reversing zone.

The location of jet reversing zone relatively to its source (and other engine elements) can be defined at the base of investigations of jet propagations in the external flow [4,5].

It is san be saying from general considerations that jet reversed when character velocity of propagated jets is decreasing to value which is neared to velocity of counter flow.

For the general reasons it is possible to tell that the stream is developed when the characteristic speed of an extending stream decreases up to the size close to speed of a counter flow.

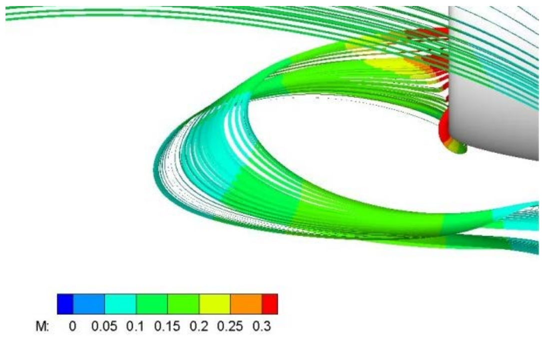


Figure 6: Flow lines for M_∞= 0.1. Color is the Mach numbers distribution along flow lines.

In the [4,5] at the base of experimental dates was find that flow reverses a jet when the flow speed is

$$u_\infty \approx 0.7 u_m \tag{1}$$

where u_m is a maximum value of speed in the jet near the reversed region.

The similar connection is demonstrated by the figure 6 where the reversed jet reversing begins at Mach number M~0.15 at counter flow Mach number M_∞= 0.1.

The same relations can be derived from the supposition that jet reversing is take place when the value of impulse flow in the jet with its lateral dimensions b is equal to the impulse flow in the part of counter flow with the same size:

$$\int_0^b \rho u^2 dy = \rho u_\infty^2 b$$

The position of jet relatively to the airplane and the engine is changed with variation of jet velocities and airplane velocities (which is the same as counter speed u_∞).
As was mentioned above the analysis is demonstrate that with the reverse activation at full thrust regime the reverse jet have a large range in spite of the large counter speed. Therefore the jet reversing zone is located far from engine air intake (figures 2, 3). With the counter speed decreasing this distance increased. After reverse take off or engine regime decreasing the jet reverse zone arrive near to inlet and in some moment pass directly under air intake. It is obvious that this is a destructive moment because the reverse jet accumulates particles in this zone during its entire operation mode.

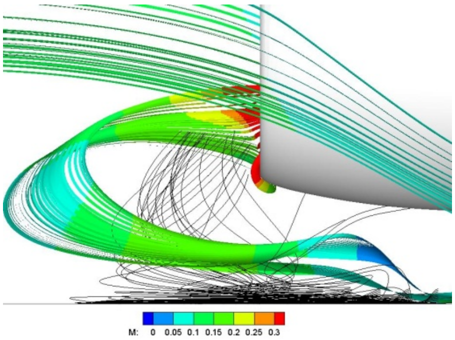


Figure 7: Flow lines (as in the figure 6) and particles trajectory (black lines).

The special calculations of particles trajectories in the conditions of the near-surface jet with the counter flow interactions were performed for analysis of this process. Results of this calculation are illustrated in the figure 7. Demonstrated particles trajectories are calculated for arbitrary initial positions. It is can be seen that particles accumulate near the region of the jet reversing.
Demonstrated at the figure 7 the flow structure is corresponding to the location of jet reversing zone near the air intake. And the vortex flow is capturing particles directly from the zone of its accumulations because of reversed jet actions.
Dangerous of this situation consists in the effect of increasing large particles transportation to engine inlet which is caused by presence of a considerable number of particles in a ground part of an ascending flow [1, 2]. Namely it is observed when the ascending flow rises from a reversed jet reversing zone.
For suppression of such danger for engine situation conservation of the sufficiently intensive jet flow regime is need for maintaining of the reversed jet reversing zone at some distance from air intake.
So the decreasing of reversed regime in correspondence with (1) must be restricted by the conditions

$$u_m \geq u_\infty / 0.7$$

which must be carry out in the near surface jet flow for maximum velocities up to a some minimum distance ΔL away from a air intake.
In [4,5] the calculation model of flow in a jet propagated along a surface in counter flow was described. This model was developed at the base of experimental investigations. At the base of this model the values of distance from a reversed jet source was determined in the assumption that

$$u_m = u_\infty / 0.7$$

In the assumption that minimum value of this distance must be correspondent to distance up to air intake then a value of reversed jet velocity u_{rw} can be determined for each value of counter flow velocity u_∞. For safety airplane motion under thrust reversing it is needed that for reverse jet velocity u_r the conditions $u_r > u_{rw}$ was performed. Determined from calculations approximated values of reversed jet velocity u_{rw} for which the reversing zone will be located under air intake for different velocities of counter flow u_∞ is illustrated at the figure 8. The region located under dashed line is corresponding to unwanted values of velocity u_r.

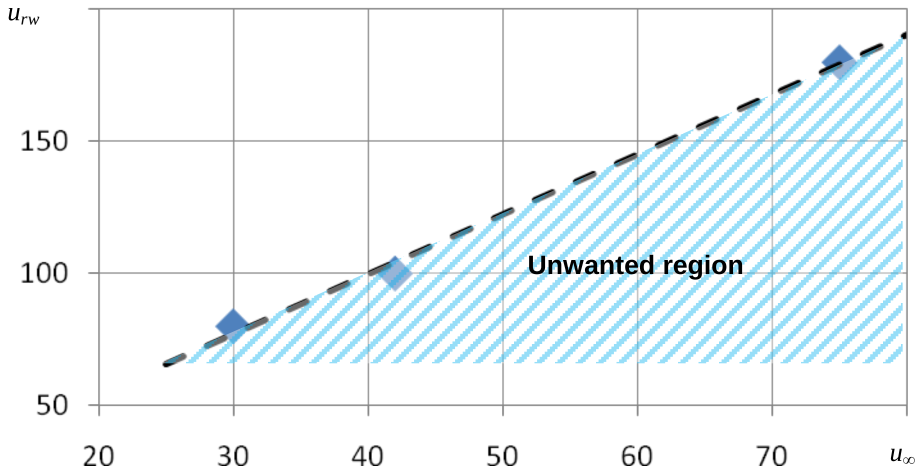


Figure 8: Dependence of the character reversed jet velocity u_{rw} from the counter flow velocity u_∞ for its reversing under air intake.

Conclusion

At the base of numerical calculations and experimental results the quality analysis of thrust reversing devices dangerous effects was performed. Particles accumulation in the zone of reversed jet reversing creates a condition for big particles suction into the engine. Probabilities of such incident sufficiently increased in the moment when air intake is located directly above this zone that is take place under thrust reversing regime changes of its take off. For reduction of this negative effect it is necessary that with decreasing a reverse regime the reversed jet velocity was such enough for reversing zone location far from air intake.

References

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