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EVALUATION OF AIRCRAFT THRUST REVERSER CASCADE CONFIGURATIONS THROUGH CFD

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Abstract. *The design of reverser systems tries to maximize the reverser thrust available. This objective is limited by several restrictions, namely: reingestion of the engine reversed gases by its own inlet affecting engine's operation; loss of efficiency of the aircraft control surfaces and spoilers; deterioration of wing and fuselage due to reverser jet impingement; and aircraft instability due to buoyancy effects on the fuselage.*

Latest reverser systems design favors blocking only the fan flow and directing it to the desired location through the use of cascades, which can locally orient the flow and avoid it from reaching undesirable places.

In this work three different cascade configurations being considered to equip the new Embraer Jet (EMB 170) were simulated through CFD (Computational Fluid Dynamics). The main objective was to anticipate if any of these configurations would cause problems to the aircraft. If the results were shown to be acceptable they would be later evaluated during ground and flight test campaign.

It was used a half model mesh of a full aircraft in landing configuration with reverser, flaps, slats, spoilers and landing gears deployed, the ground was considered as well. The half model numerical mesh has 1.4 million tetrahedral elements. A commercial CFD software was used with a density based coupled solver and realizable k-e turbulence model.

This numerical approach was shown to be a very cost effective way of testing many different reverser cascade configurations reducing inherent flight test risks. Understanding how the aircraft is affected by the thrust reverser allowed a better design of the aircraft test campaign and also increased aircraft testing safety since the reverser efflux patterns were understood and test pilots warned about any controllability issues they could face.

Keywords*. Aircraft, Engine, Propulsion, Thrust Reverser, CFD*

1. Introduction

Modern jet aircraft usually have thrust reverser systems in order to decelerate the aircraft more quickly and efficiently. This system was first introduced in propeller driven aircrafts by the reverse pitch, where the propellers relative angle of attack were is changed to negative, therefore turning thrust direction opposite to aircraft direction. Compared to propellers the reverser of jet aircrafts usually has the same functionalities and requirements, but the jet aircrafts have a higher landing speed that puts a greater burden on the landing gear brakes. Having a thrust reverser system, despite of the extra complexity and weight of the nacelle and added maintenance costs, lowers brake wearing, diminishes the time waiting to cool down brakes and, above all, the thrust reverser let landings and takeoffs be performed in shorter runways, increasing the range of airports where an aircraft can operate and improving aircraft safety.

Jet aircrafts reverser systems work on the engine jet flow through some kind of blocking surface that drives its internal flow in the aircraft opposite direction. Thrust reverser systems can block either the fan and core flows or only the fan flow. There are basically two different kinds of thrust reverser systems on jet aircrafts (Treager, 1996):

- Post exit or target type: the exhaust jet stream is blocked
- Pre exit type: uses cascades or blocking/deflectors doors, the jet flow is blocked before it exits the nozzle being directed to an alternative exit.

Figure (1) shows a pre exit type of reverser with cascades stowed and deployed, similar to the one considered in this paper. It can be seen that even when the reverser is deployed there is a forward component of thrust through the engine primary core.

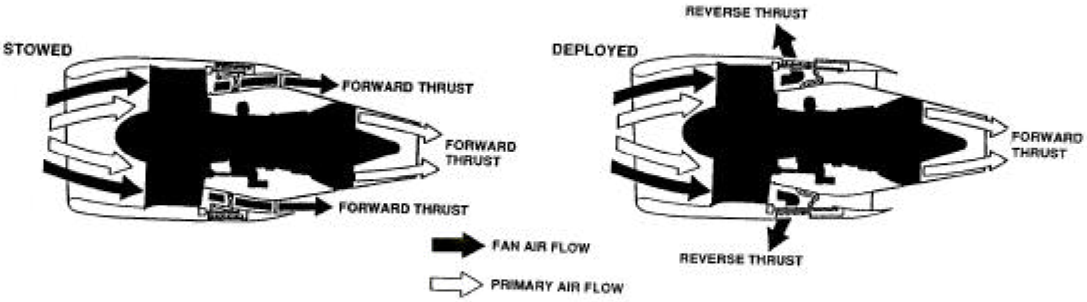


Figure 1. Pre exit reverser type using cascades at stowed and deployed positions.

Generally the thrust reverser system is designed to provide as much reversed thrust as possible. The thrust limits are associated with several constrains, such as:

- Reingestion – if the flow is over turned to the front in a sharp angle it can be reingested by the engine inlet leading to stability problems like engine surge, stall, inlet distortion and noise. Reingestion is basically a function of aircraft speed, the lower the speed the higher the chances of reingestion. Therefore, normally, the aircraft and engine manufacturers impose an aircraft low speed limitation for the use of reverse. This speed limitation correspond to the point where the thrust reversed is considerably reduced, it is called “cut off speed”.
- Foreign object damage (FOD) – reversed flow directed to the ground tends to create a strong inlet-ground vortex that can lift debris that are easily trapped into the inlet flow and may deeply damage the turbomachinery.
- Loss of efficiency of the control surfaces and spoilers – the reversed flow may substantially change the flow characteristics on these surfaces, leading to aircraft stability problems and spoilers drag wipe out.
- Impingement – reversed flow impacting the fuselage, wing and slats cause vibration that can deteriorate these surfaces, affect slat actuators and cause noise and discomfort to passengers.
- Buoyancy – part of the reversed flow from both sides of aircraft will meet below the fuselage. This cause a higher pressure on the fuselage bottom surface, which depending on its intensity and location can cause loss of controllability by tending to lift the aircraft nose landing gear.

One of the solutions to minimize thrust reverser problems, improving efficiency and control over the direction of the reversed flow is the use of cascade boxes – vanes grouped together into rectangular boxes located circumferentially around the nacelle. The reverser is then comprised of different cascade boxes, each one with its own vane angles that turn the flow to pre-defined circumferential and axial directions (see Fig. 2). This makes possible to tackle each of the constraints mentioned above, providing the required overall negative thrust. There are 3 different solutions that can be implemented on a particular cascade box:

- Close a box – usually done on the bottom side of the nacelle to avoid debris lifting and FOD.
- Change the angle axially – in order to avoid reingestion or increase reverser thrust.
- Change the angle radially – in order to avoid the jet impingement on particular surfaces.

In all the cases the cascade configuration must be such that during the period of reversing neither engine operating point nor the nacelle internal flow quality should be adversely affected.

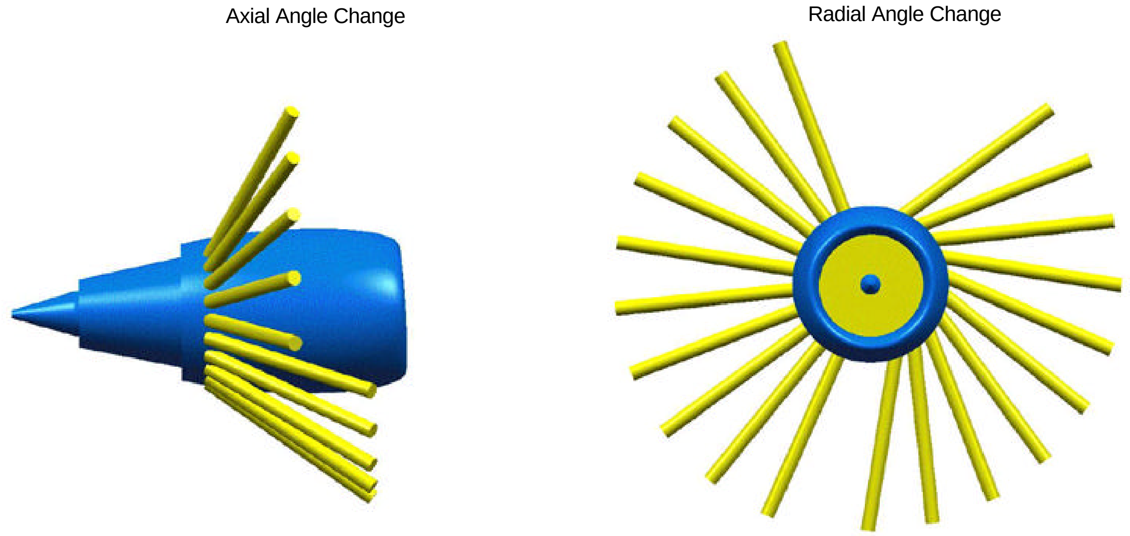


Figure 2. Cascade boxes angles changed axially and radially respectively (20 boxes – 10 per nacelle side)

The thrust reverser wind tunnel tests are typically used to provide valuable information for the cascade configuration design. Fan operating point, noise impacts, reversed thrust and ideal engine thrust setting are some of the important data that can be gathered during wind tunnel tests (Dietrich & Gutierrez, 1974; Dietrich and all. 1975). On the other hand, there are several drawbacks associated to thrust reverser wind tunnel tests (Chuck, 2001): problems due to scaling and accuracy of model measurements; difficult to visualize the entire flow field of the plumes in the wind tunnel environment; high cost and high turn-around time; performed generally late on the design phase rather then earlier when it could provide design guidance. The use of CFD tools as a guidance in order to anticipate problems with cascade configurations seems to be an attractive option. This approach can provide a fairly good idea of the flow field complexity with easy visualization of individual cascade influence, while allowing for testing many different configurations.

This work presents the set of numerical analyses carried out for the reverser evaluation of the Embraer 170 Jet. The main objective of the study was to anticipate, through CFD, potential problems with the cascades selected to be the tested on the aircraft. A preliminary design was performed by the engine/nacelle and aircraft manufacturers based on their previous experience, reverser thrust stand tests and the engine thermodynamical cycle deck. At the beginning of the conceptual and definition phase there were about 50 different cascade boxes configurations considered. Each one of them was tested individually in a thrust test bench. Based on obtained results the 6 best configurations were selected and 3 of them chosen for development test on the aircraft during ground and flight test campaign. These designs presented the best trade off between reversed thrust and ability to overcome aircraft and engine operational problems.

2.2. The CFD analysis

The condition chosen for analysis was the aircraft at its landing configuration with its speed equal to the thrust reverser cut off speed (60 knots). The low speed is more critical for engine reingestion and buoyancy, besides this, at this condition the fact of having flaps, slats and spoilers deployed increases the possibility of impingement. The aircraft is supposed to be on an airport runway at sea level on a standard temperature ISA day.

Since the reverser flow may affect almost all aircraft main components it was decided to mesh the whole aircraft, as complete as possible. Hence, besides fuselage, wing, pylon, nacelle and tail, the mesh included the ground plane, the landing gear, spoilers, flaps, slats and, of course, the thrust reverser deployed. Initial evaluation did not require the assessment of cross wind effects therefore only half aircraft model with symmetry was used. The mesh comprised about 1.4 million tetrahedral elements adapted to y+ in most of main interest wall regions. Because most of the potential problems occur in the wing inboard side and the reversed flow is directed towards the front of the aircraft, the region limited by the engine and aircraft symmetry plane, between the wing and nose landing gear was more refined than the rest of the domain. The landing gear geometry was simplified and the flap track fairings and winglets were not included.

Figure (3) shows the computation domain and Fig. (4) shows some mesh details near the engine.

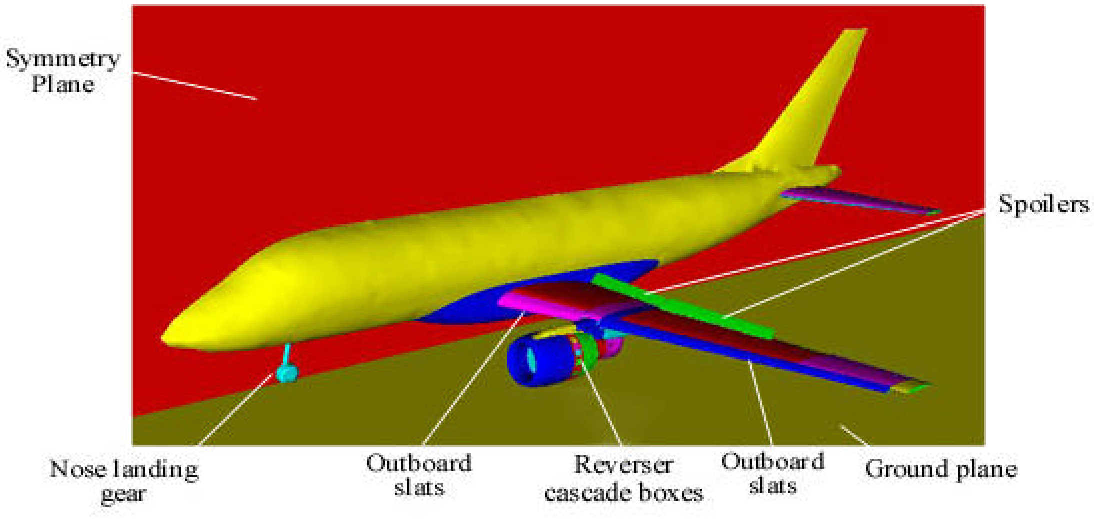


Figure 3. Aircraft model.

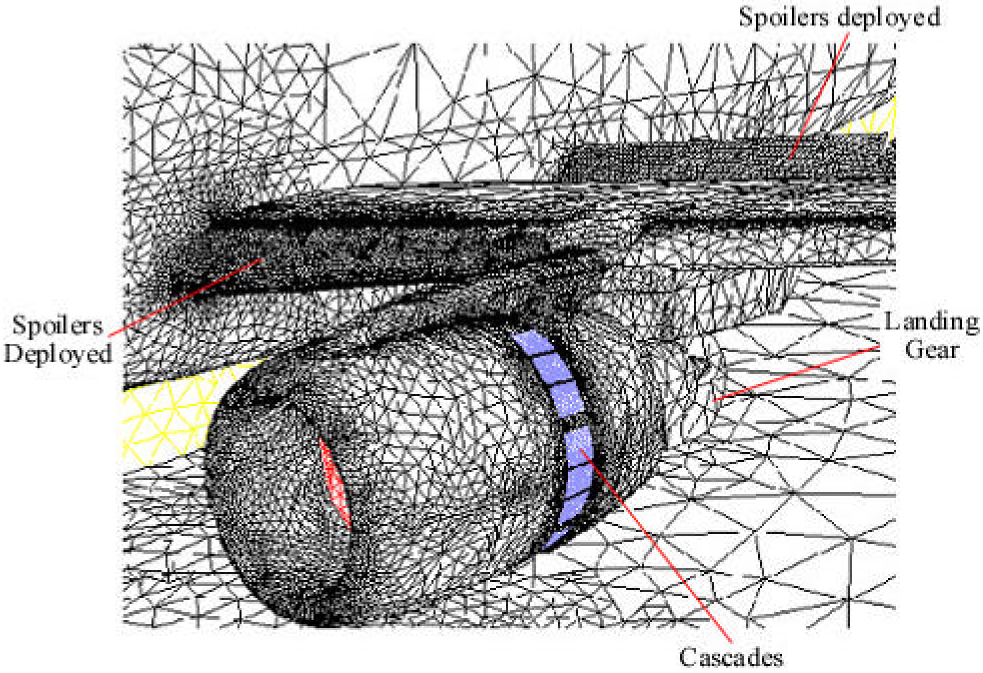


Figure 4. Detail of aircraft mesh.

The Reynolds averaged Navier-Stokes equations were solved for an ideal gas, with a coupled density based, finite volume formulation, upwind scheme with second order spatial interpolation and turbulence closure through the realizable k-ε model. Boundary conditions were set individually for each of the 18 engine's cascades in terms of total pressure, total temperature and flow angles, so that the maximum reverser thrust was obtained with the right efflux mass flow and pattern. The fan inlet and exhaust jet conditions were imposed according to on the engine thermodynamic cycle deck. The ground was treated as a moving wall at 60 kts, outer boundaries were treated as pressure farfield inlet/outlet boundary condition with 60kts flow speed, null angle of attack and sea level standard atmosphere pressure and temperature conditions.

2.3. Results

Three thrust reverser cascade configurations were tested. The results for the so called "baseline configuration" will be presented first. Afterwards the comparison between the three tested configurations will be shown.

Figure (5) shows an isosurface of total temperature just above ambient temperature. This is a spatial way to visualize the envelope affected by the reverser plume. It can be seen that a reasonable part of the bottom of the forward fuselage is under the influence of the reverser efflux, this may indicate the presence of buoyancy and controllability problems. On the other hand there is no risk of reingestion by the engine inlet. It can also be noticed that the region below the nacelle is not affected by the reverser flow, meaning that there is a very low probability of having the efflux pushing debris from the ground into the inlet flow, i.e. chances of foreign object damage (FOD) are low. Figure (5) also shows that the reversed flow encompasses part of the flaps, slats, spoilers and horizontal tail. If this means direct impingement there may be damage to the fuselage and wing surfaces.

Figure (6) shows streamlines originated on the reverser cascades colored by velocity magnitude. Comparison of Fig. (5) and Fig. (6) indicates that the volume encompassed by the isosurface is bigger than the one occupied by the streamlines, this is due to the recirculations induced on the front of the reverser flow that diffuses the flow temperature to the front. It can be confirmed, from Fig. (6) that there is no reingestion at the fan inlet. Moreover, this streamline analysis shows that actually the reverser flow meets the symmetry plane far from the nose landing gear, considerably reducing the expected buoyancy effects.

Figure 5. Thrust reverser plume - isosurface of total temperature.

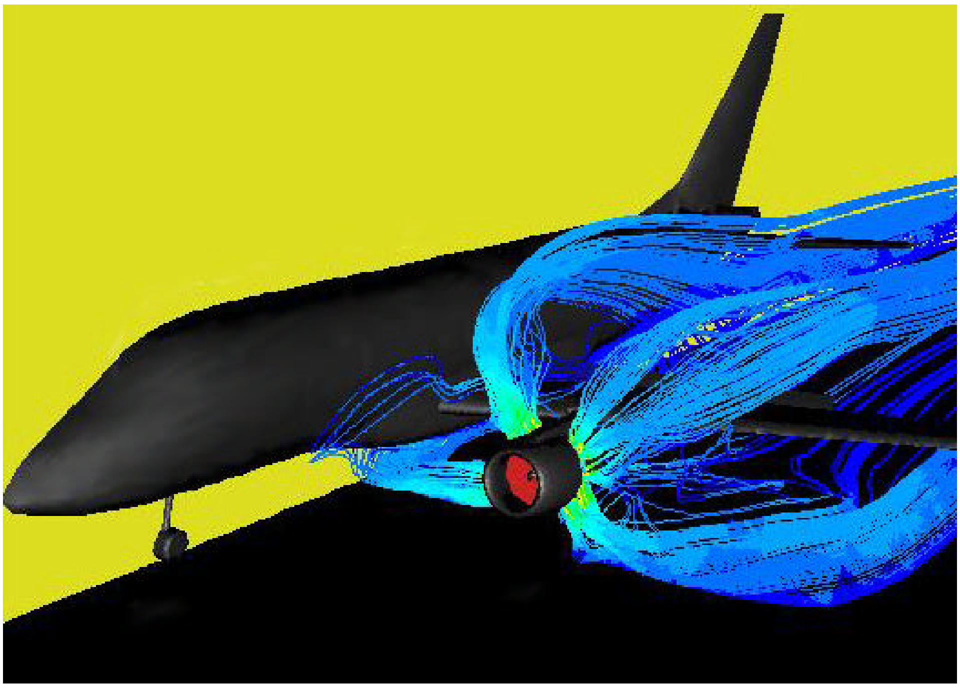


Figure 6. Thrust reverser streamlines colored by velocity magnitude.

Figure (7) shows a front view of the Fig. (6) picture. It can be noticed that at the bottom of the nacelle the reverser cascade boxes are blocked in order to avoid FOD. The pylon blocks the upper region as well. The outboard part of the thrust reverser is located further away from the wing and direction of the flow path is not of concern, the main objective is to maximize reverser thrust at this side while avoiding reingestion and extremely large thrust asymmetry in case one engine fails. On the inboard, the reverser flow should not hit the side fuselage and the slats directly. It can be seen from Fig. (7) that this objective was attained at least in what concerns the fuselage.

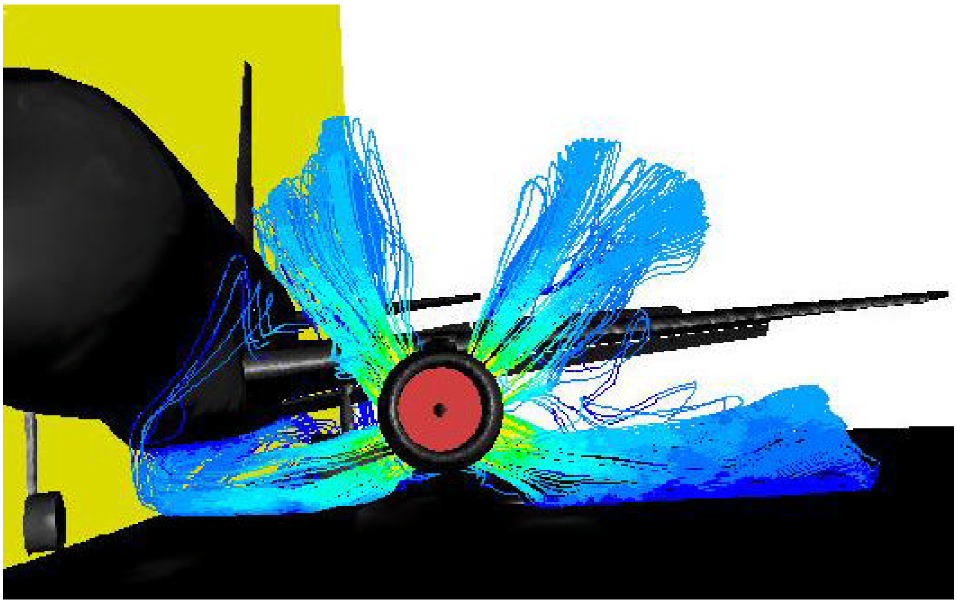


Figure 7. Front view of the engine with thrust reverser streamlines colored by velocity magnitude.

Figure (8) show streamlines that pass through the spoilers. The thrust reverser affects only a small part of the flow that reaches the outboard spoiler. On the other hand the inboard spoiler flow is reasonably affected by the reverser efflux, meaning that the performance of the inboard spoiler will be probably reduced at this condition.

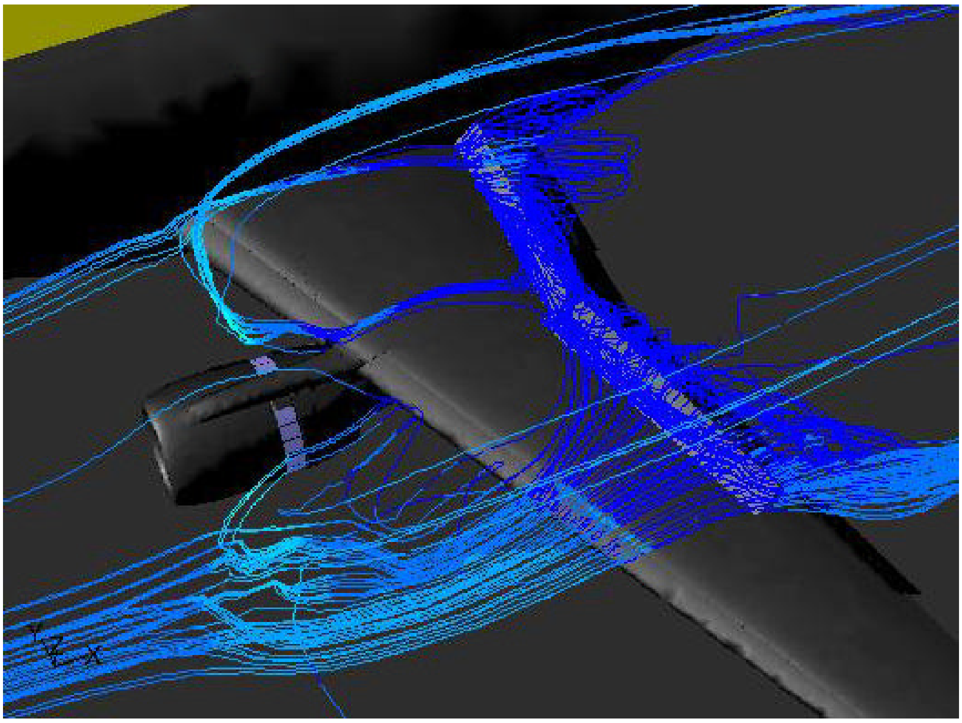


Figure 8. Streamlines released from the spoilers.

Figure (9) presents isocontours of total temperature. The minimum temperature on the scale (blue) is ambient temperature and the maximum temperature (red) is the reverser outlet temperature. Higher temperatures on the ground besides the engine mean direct impingement of the reversed flow. The wings have only a small increase in temperature, greater temperatures are seen at the inboard and nearby the fuselage. This indicates that the reversed flow is just passing close to these regions without impingement, but some small vibration and noise levels may be expected. The high temperatures shown at the pylon back are not due to the reverser flow but to the engine core exhaust flow.

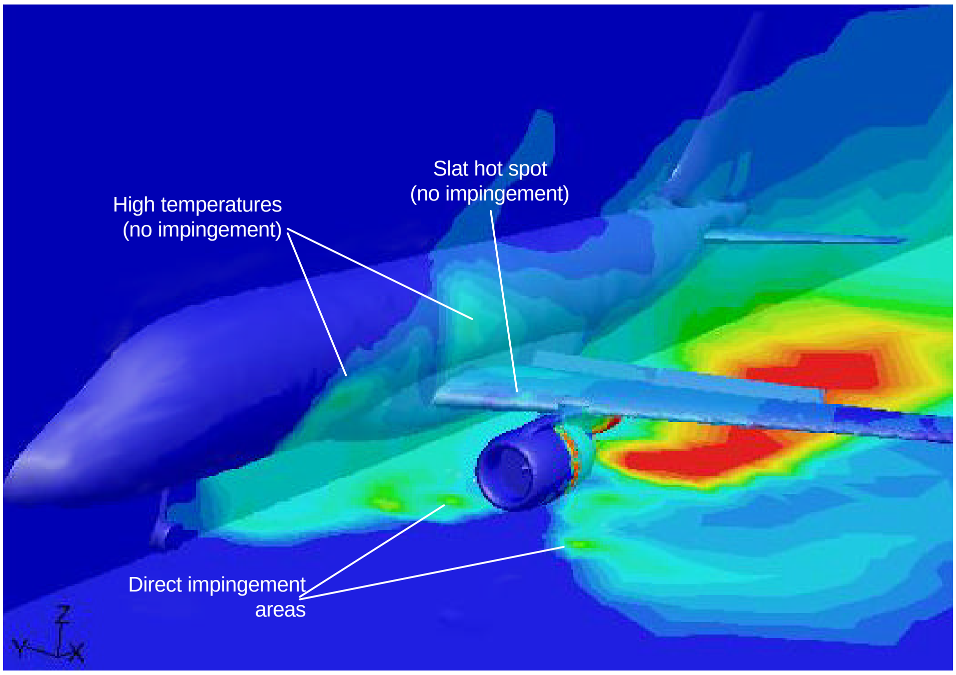


Figure 9. Isocontours of total temperature.

Figure 10. shows a detail of the model nearby the engine. It can be noticed that just a small part of the nacelle before the reverser is heated by the reverser flow, the whole inlet is at ambient temperature. The slat analysis shows a warmer spot which mean the reverser flow is passing nearby, minor vibration may be expected on the slat actuators.

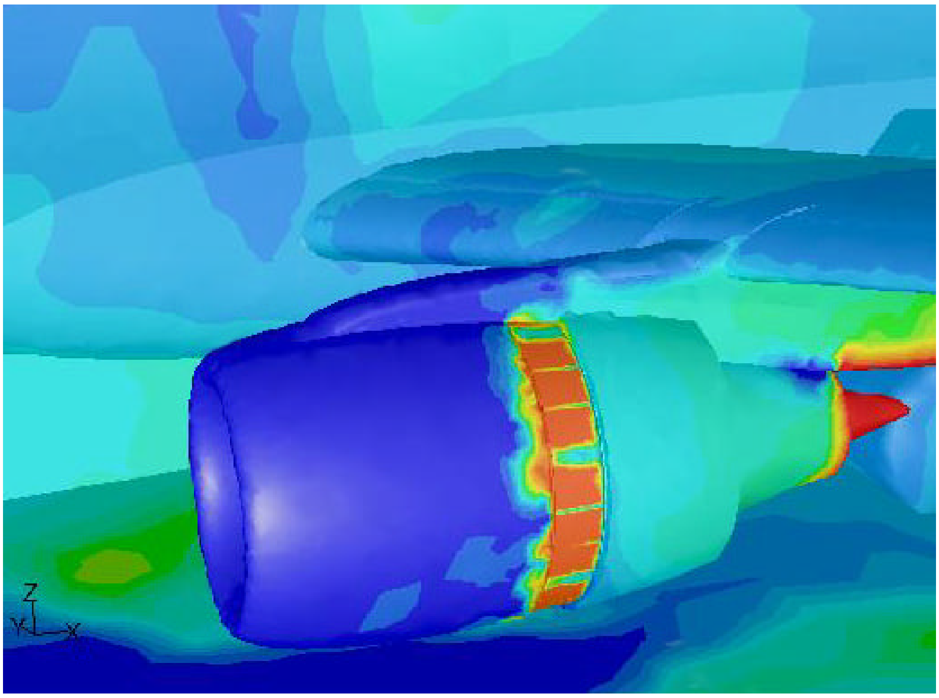


Figure 10. Detail of isocontours of total temperature at the nacelle, pylon and wing.

Figure (11) shows the static pressure distribution. It can be seen some spots of high pressure on the ground, fuselage and inboard slats confirming that the reverser flow is passing nearby. It is interesting to highlight the high static pressure seen on the bottom of the fuselage. It is important to notice that this impingement region was kept far from the nose landing gear, so that no buoyancy problems are expected. Also on the nacelle external cowl, before the cascades there are some spots of high static pressure, these are due to the free stream stagnation region, where the free stream flow meets the thrust reverser flow in the presence of reverser flow.

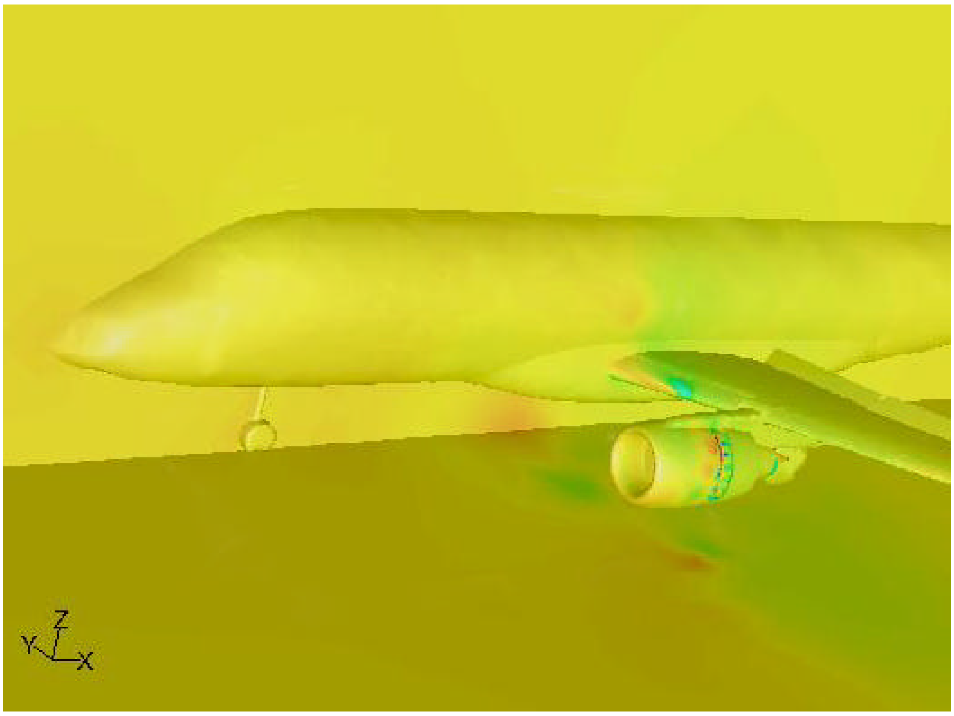


Figure 11. Isocontours of static temperature.

The contours of transversal to forward velocity ratio (V_y/V_x) and vertical to forward velocity ratio (V_z/V_x) on a longitudinal cross section plane just before the empennages are presented on Fig. (12). The cross section was mirrored here only for clearer visualization purposes. The scale of the contours of both figures varies from 0 to 0.2, what corresponds to variation in the angle of attack (function of V_z/V_x) and sideslip angle (function of V_y/V_x) for the empennages from 0 to 11.3°. The results show that the higher sideslip angles are observed close to the horizontal stabilizer, far from the vertical tail, so no lateral stability problems are to be expected. In the same way, the high angle of attack regions are far from the horizontal tail. Therefore it may be expected that the horizontal stabilizer will keep its efficiency on the ground.

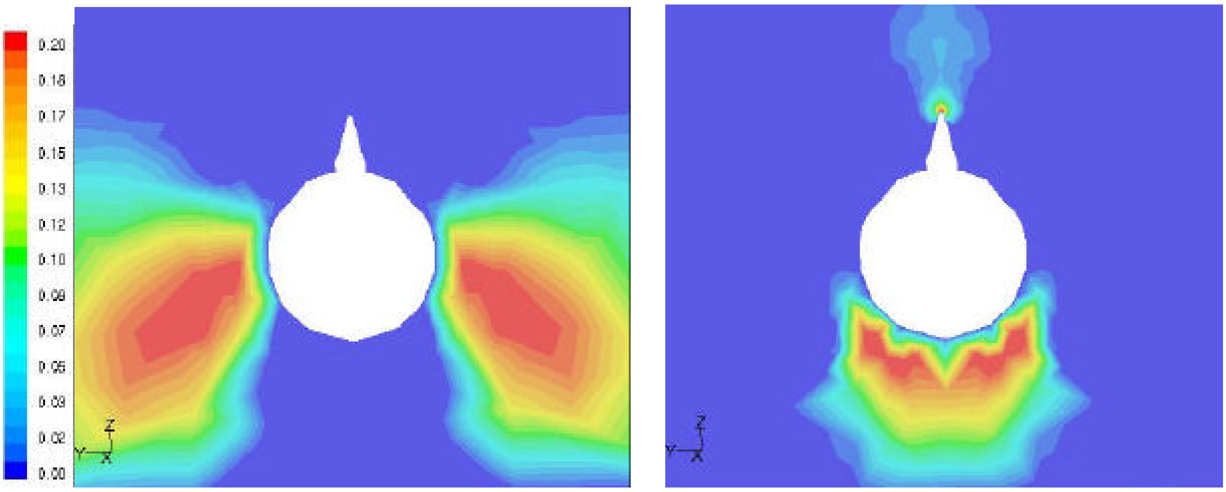
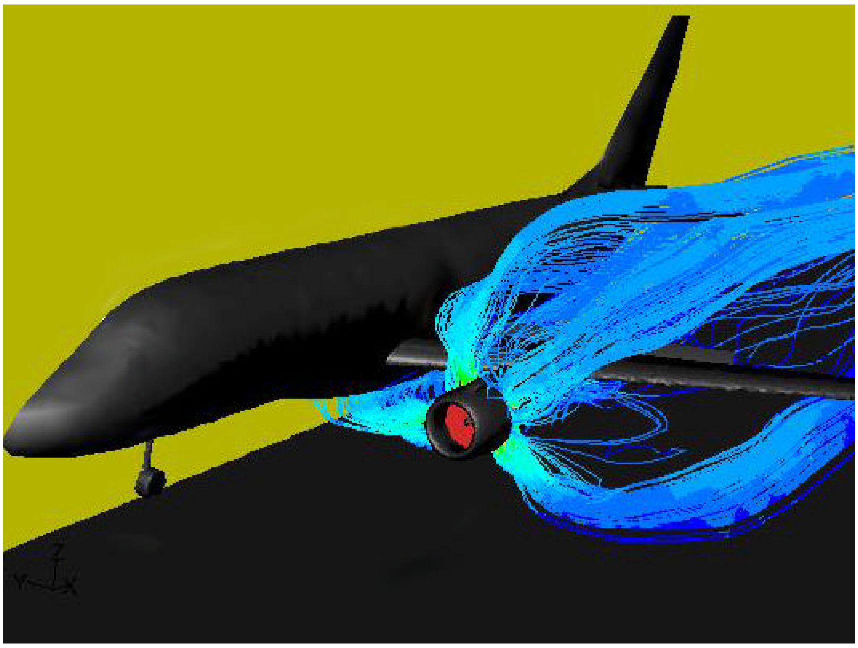


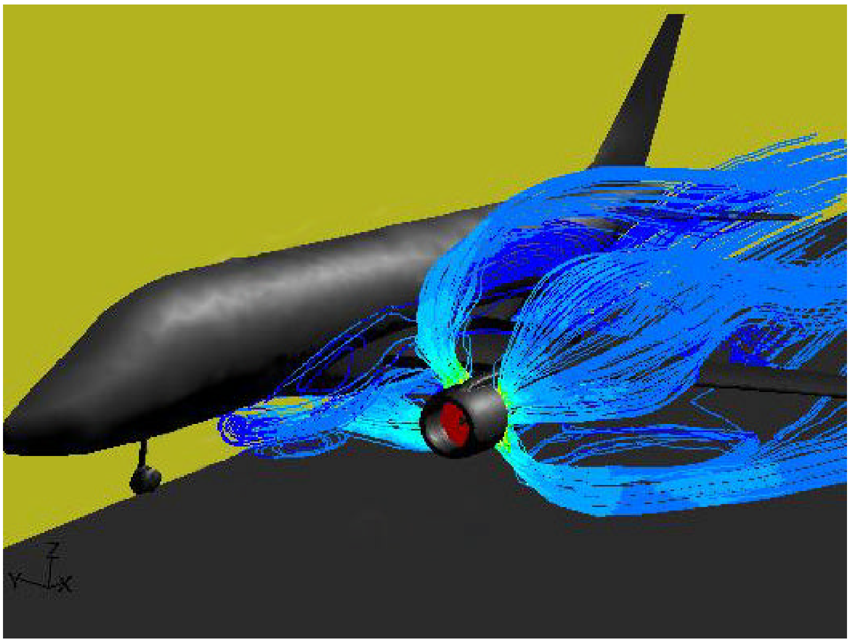
Figure 12. Contours of V_y/V_x (left) and V_z/V_x (right) on a plane just before the empennage.

The CFD analysis of the EMB 170 was also performed on two other configurations. The difference between the baseline and these configurations are the different angles at the lower inboard boxes. The cascade vanes forward angles at this region were reduced, the objective is to have less probability of reingestion and buoyancy problems comparing to the baseline configuration. Therefore in case any of these issues is detected during flight test with the baseline cascade set, the use of the alterative configurations would correct the problems. But these lower cascade vanes forward angles also reduce reversed thrust available, thus one of the alternative configurations has greater engine speeds than the other configurations in order to recover the original thrust.

The path lines released from the thrust reverser cascades, colored by velocity magnitude for these two other reverser cascade configurations are shown on Fig. (13). Because the lower inboard cascade angles are less forward than the baseline configuration, see Fig. (6), the flow meets the fuselage slightly closer to the wing root. Comparing the both alternative configurations the second configuration has the same angles of the previous one, but engine thrust is increased, therefore the flow leaves the cascades with higher speeds and the reverser plume is more open. Therefore on the inboard the flow hits the symmetry plane almost normal to it and with higher momentum, which induces flow recirculation that can be seen on the front of the second figure. Because of the higher thrust and the higher speed with which the flow leaves the engine this last configuration has a more open plume and the pressures on the fuselage and on the outboard slats are also increased.



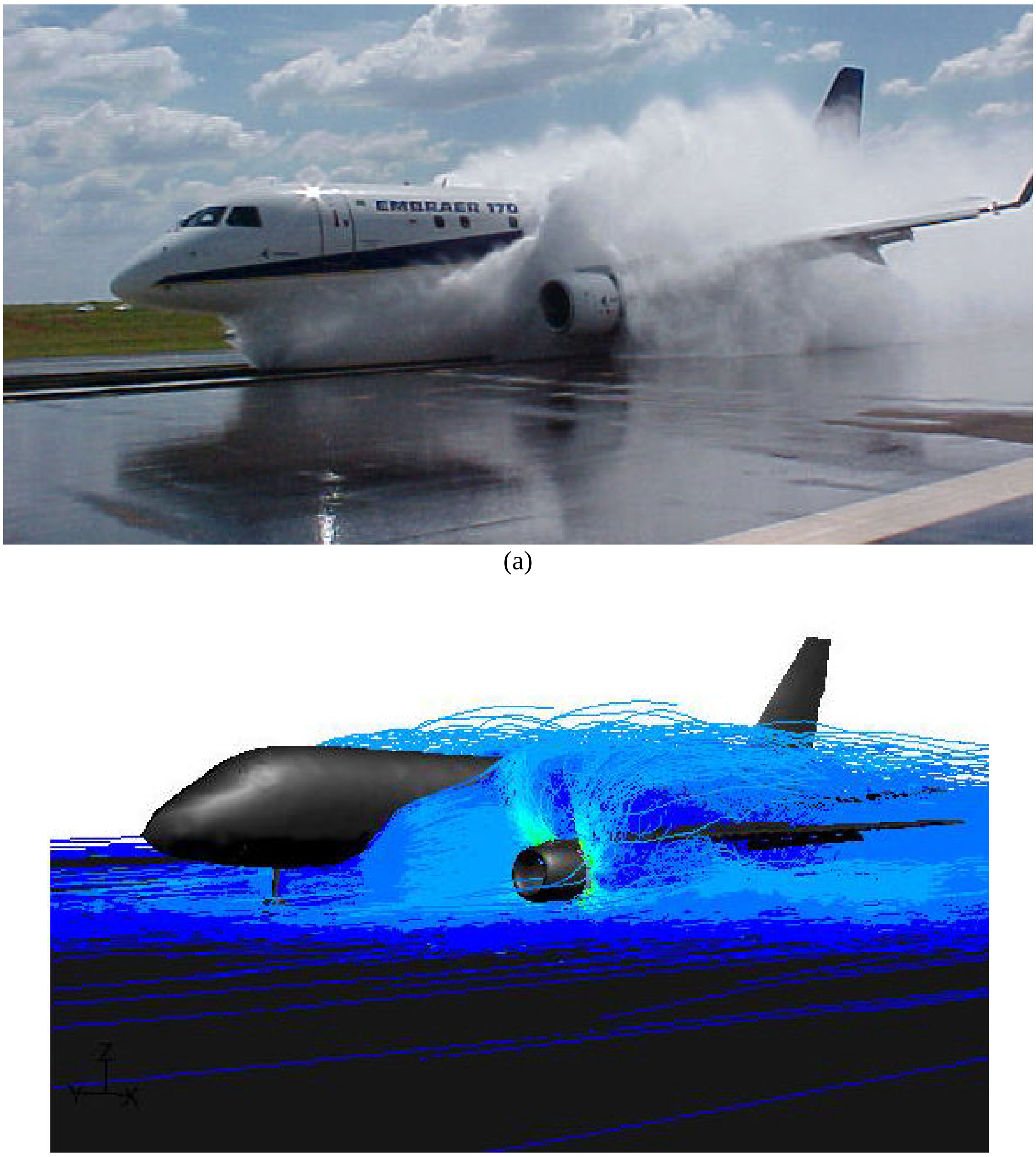
(a)



(b)

Figure 13. Path lines for the two alternative thrust reverser cascade configurations.

Aircraft landing on wet runways affects aircraft operation, including the engine. Thus, certification tests are required at many different aircraft and engine configurations, including the use of thrust reverser. Some of these tests have already been performed. Figure (14) shows the water spray cloud generated during one of these tests using the reverser and, as well as, a CFD result containing the trajectory of 10 µm water droplets released just above the ground, colored by velocity magnitude. It can be seen that, even though a water spray assessment was not the objective of this certification test analysis, this enabled a qualitative comparison of numerical and experimental results. One can noticed that both fig. (a) and (b) suggest a quite similar path for the water particles.



(a)

(b)

Figure 14. (a) Water spray test on EMB 170 aircraft and (b) 10 μm droplets trajectory released from the ground in the CFD analysis.

4. Conclusions

A new methodology was presented based on CFD analysis to check thrust reverser cascade configurations before flight test is performed on the aircraft, therefore lowering development risks at low cost and increasing test campaign safety. This approach has helped understanding of the physics involved on the particular thrust reverser cascade configurations being used on the Embraer 170 jet.

The CFD analysis has shown that while the baseline configuration presents little chances of reingestion and FOD, buoyancy effects are low, spoilers and tail performance is not affected, attention must be taken during flight test on the inboard slats and the fuselage regions besides the engine inlet and above the wing.

Other two cascade configurations were tested, with smaller chances of reingestion on the inboard and less buoyancy, but with similar concerns of the baseline configuration. The first alternative to the baseline has lower reversed thrust, the second one indicates more impingement on the fuselage and outboard slats with similar thrust to the baseline configuration.

Comparison of water spray tests performed on the EMB 170 and CFD analysis of the thrust reverser that flow field overall trends may be well captured with CFD.

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