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Wind Tunnel Tests Results and Performance of the MOTHIF blown flap

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1. Introduction

Enhancing global connectivity means increasing aircrafts' operability over airports with reduced take-off runaway length. This STOL target is crucial to meet the European FlightPath 2050 connectivity goal, which points out an increasing interest in Small Air Transportation (SAT). This connectivity goal aims to let European citizen, wherever they live, to reach any desired destination within Europe in 4 hours: this is called the "d2d 4h" target [3].

Pursuing this target means designing aircraft capable to lift off over runaway shorter than 800m. To achieve this challenging take-off performance, a high lift system capable of generating high lift coefficients without penalizing the configuration drag, weight and complexity, should be designed.

Thanks to the funding received from the Clean Sky 2 Joint Undertaking (JU), which is supported by the European Union's Horizon 2020 research and innovation program, an innovative high lift device has been designed and developed within the frame of the project MOTHIF (Model Testing of High LiFt system).

The MOTHIF project established a collaboration between Piaggio Aerospace and the MOTHIF consortium, composed by von Karman Institute (VKI) and SONACA, and it aims to test a blown flap device, designed by Piaggio, to allow STOL capabilities of a future affordable and green commuter belonging to EASA CS 23.

The blowing system has been designed to obtain a considerable lift increase when working, but without penalizing performance in case of blowing system failure. The blown flow is acting mainly on the main airfoil, activating a supercirculation because of a suction effect of the boundary layer. This design choice was made to keep the unavoidable increase in pitching moment very low, thus reducing the trim drag effect and allowing acceptable take-off performance of the aircraft even in the event of a blowing failure.

Piaggio designed the trailing edge blowing system integrated inside an ad-hoc airfoil, specifically developed for the mission requirements, with a Fowler flap implemented, being also responsible for the SLS ALM manufacturing of MOTHIF's trailing edge module with pressure taps and blowing piping.

SONACA manufactured and provided model integration with Piaggio trailing edge modules, while VKI instrumented and tested the model inside its L1-A subsonic wind tunnel facility.

The target of the wind tunnel tests has been to substantiate bi-dimensional flow performance of the blowing system, nurturing a better comprehension of the supercirculation effectiveness and its dependency to different physical parameters, for different free stream speeds, angles of attack (AoA), flap deflection and blown flow speed.

This paper aims is to present and discuss the results coming from the wind tunnel test (WTT) campaign, which took place between April and July 2021 at VKI. Furthermore, a comparison with the expected results, coming from CFD analysis ran during the design phase, is exposed to give consistency and a deeper explanation of the wind tunnel results.

2. The MOTHIF specimen

A 1.5m x 1,35m wing/flap model has been designed, built and then tested in the VKI large subsonic L1-A wind tunnel.

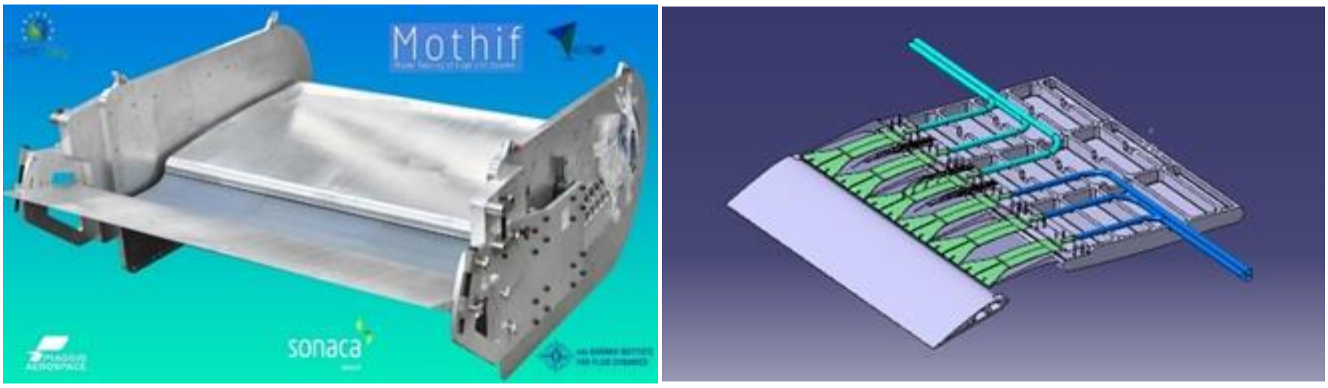

Figure 1 - WT specimen manufactured model (left) and CAD geometry (right)

The specimen has the ability to provide, alongside different angles of attack, several flap deflections: 15°, 20° (also named Take Off configuration) and 30° (named Landing Configuration).
In addition, the specimen provides different flap gap positions, suitable for wind tunnel optimization (for additional information, see [4]).

3. The Wind Tunnel Arrangement

VKI L1-A Wind Tunnel test chamber is an open section one. In order to provide bi-dimensional flow over the specimen, the test chamber has been equipped with endplates, based on CFD simulations results of the wind tunnel itself [1]

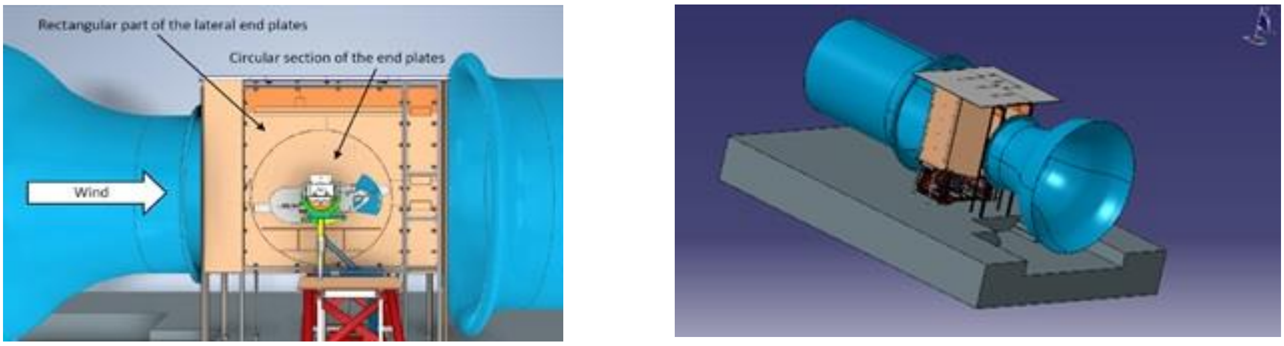

Figure 2 - CAD model of the wind tunnel arrangement

Figure 3 - MOTHIF model inside the wind tunnel test chamber

WTT is equipped with both force balance and pressure sensors data: coefficients used in this paper are those coming from the balance, and have been compared with those obtained integrating the pressure data for cross-checking.
[Ref.1] shows a very good agreement between the WT experiment and its CFD simulation, substantiating the validity of the simulation approach used for the evaluation of the flapped configuration performance in free air flight.

4. CFD based data

The wind tunnel tests data will be presented in comparison with the CFD results obtained during the design phase of the model for a cross-check of the benefits of an active blowing jet in increasing lifting capabilities. Simulation CFD software has been Metacomp CFD++ [5].
CFD data considered for the comparison are those coming from 3D simulations, which are geometrically representative of the MOTHIF model. The 3D simulation is mandatory because the blown jet, which exits from several ducts, does not act uniformly on the entire wing span.
The bi-dimensionality of the flow around the model, which is the wind tunnel test target, is ensured in CFD simulations by appropriate side boundary conditions.

5. Blowing Flow Parameters

Blown flow speed is set through the pressure ratio between ambient and a reservoir, which is feeding the blowing system.
The tested pressure ratios (PR) have been:

- 1.3
- 1.48
- 1.7

As for the one-dimensional theory of the flow inside a converging duct, the maximum speed is obtained at the smallest section and it depends only on the total pressure ratio between reservoir and exit.

The isentropic formula is:

$$Mout = \sqrt{\frac{2\left(\frac{P_0}{P_{amb}}^{\frac{\gamma-1}{\gamma}} - 1\right)}{\gamma - 1}}$$

The maximum pressure ratio, so 1.7, leads to M=0.9 at the exit.
From CFD analysis, the following mass flow for the blowing system at the different pressure ratios is obtained and then compared with respect to WTT based results:

MFR for the MOTHIF Specimen	Pressure ratio		
	1.3	**1.48**	**1.7**
CFD based MFR [kg/s]	0.354	0.45	0.558
WTT results MFR [kg/s]	0.305	0.4074	0.51
Delta WTT vs CFD [%]	-13.8%	-9.5%	-8.6%

Table 1 – Mass flow rate comparison between CFD and WTT experimental data

Mass flow values depend on the speed at the diffusor outlet and by the outlet area geometric characteristics.
Since geometric characteristics are given and are the same between the WTT specimen and CFD model, it means that the simulation jet speed is very similar to the WTT one: this is an additional validation of the boundary conditions used during the simulation and of the simulation accuracy itself.

6. Wind Tunnel Test Matrix

Here below the WTT matrix performed at VKI:

Flap [°]	Gap [%]	Angle of Attack [°]	Wind Tunnel Speed [m/s]	Pressure Ratio
15°	2% 3% 5% 7%	4 8 11 13 14 15	20 30 35 40 42,5	1 1,3 1,48
20°	3%	4 8 11 13 14 15	20 30 35 40 42,5	1 1,3 1,48 1.7
30°	3%	4 8 11 13 14 15	20 30 35 40 42,5	1 1,3 1,48 1.7

Table 2 – Wind tunnel tests matrix

7. Flap Gap optimization

Firstly, the wind tunnel provides flap gap optimization. The optimization was performed at flap deflection=15° and then compared with the CFD results obtained during the design phase.

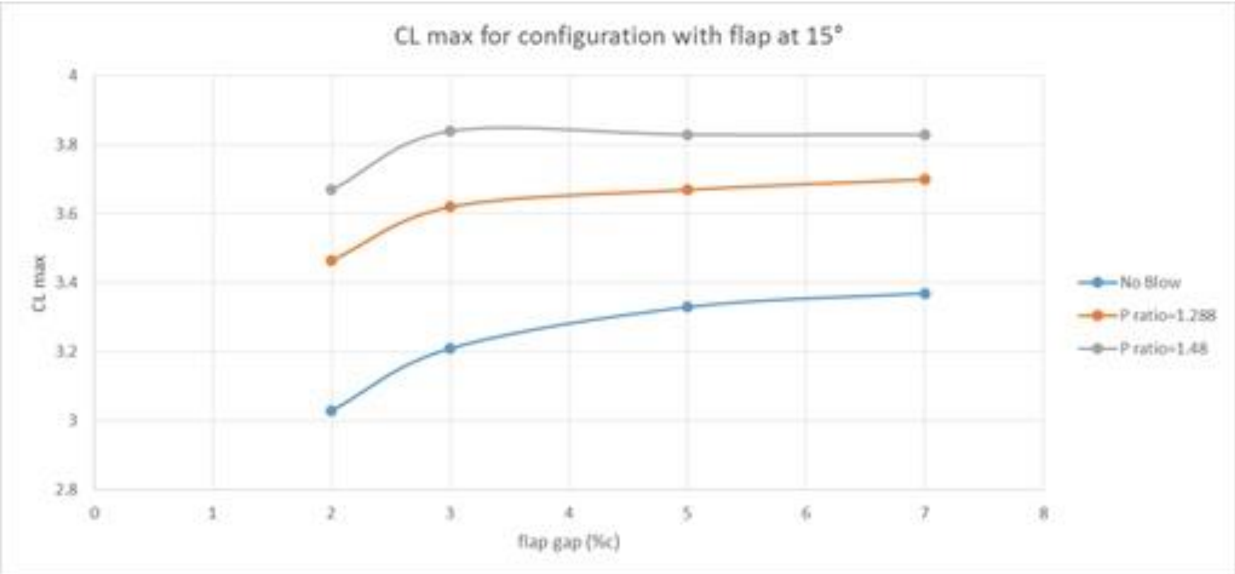

Figure 4 - Flap=15°, CFD Simulation: CL max with respect to the flap gap, for different pressure ratios

The target of the optimization is to have the maximum lift increase, so the higher value of CL, but without penalizing two important features:

- The pitching moment: it has to be maintained as low as possible, so that the extra lift generation corresponds to a smaller trim drag
- The performance in blow-off conditions: when the blowing system fails, the high lift system needs to generate a suitable amount of lift. This is a fail-safe design criterion.

WTT, done at both 20 m/s and 42,5 m/s, result in:

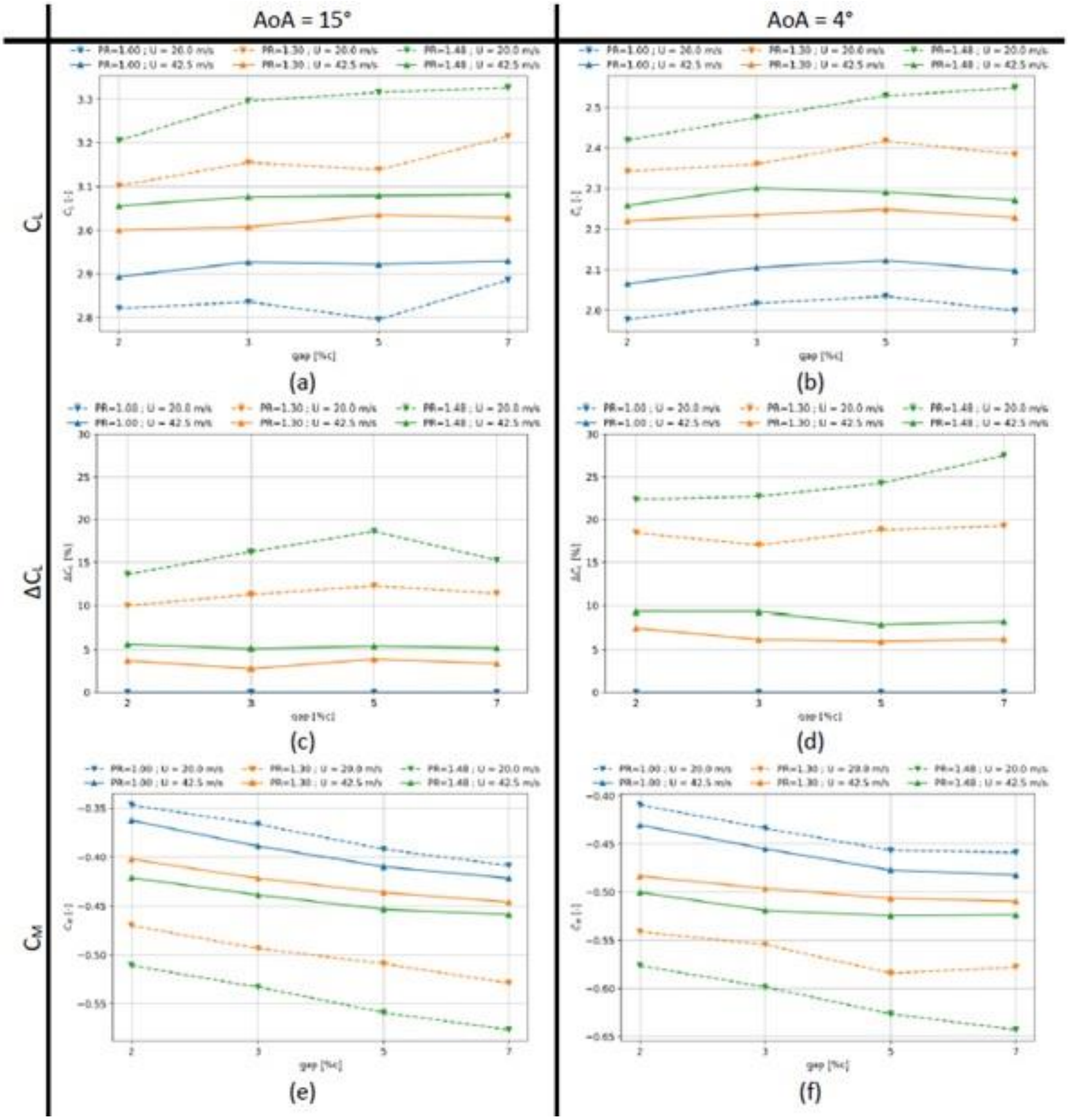

Figure 5 -Forces acting on MOTHIF wing model for AoA=15° (a)(c)(e) and AoA=4° (b)(d)(f) at 20m/s (dashed curve) and 42.5 m/s (full curve) for PR=1 (blue), 1.3 (orange) and 1.48 (green)

It can be concluded that:

- In the "no blow" condition, the larger the gap, the better the flaps lifting capabilities,
- Furthermore, the larger the gap, the larger the pitching moment, in absolute value, and therefore the larger the trim needed by the airplane and the consequent increase of drag.

The best compromise between the configurations tested appears to be gap=3%, since it presents good lift capabilities (both regarding blow-off conditions and ∆CL due to the jet) while limiting the increase of the pitching moment and the consequent airplane trim drag.
This result confirms and substantiates the CFD outcomes over the gap value during the design phase.

8. Take-Off Configuration Results (Flap=20°)

As visible in the text matrix, WTT provides different free stream speed tests.

Before exposing results, it is useful to show the influence of the free stream speed on the blowing jet deflection and its effectiveness. As visible from the smoke visualization from WTT, changing the free stream speed, the blowing jet deflection angle changes too, at each pressure ratio:

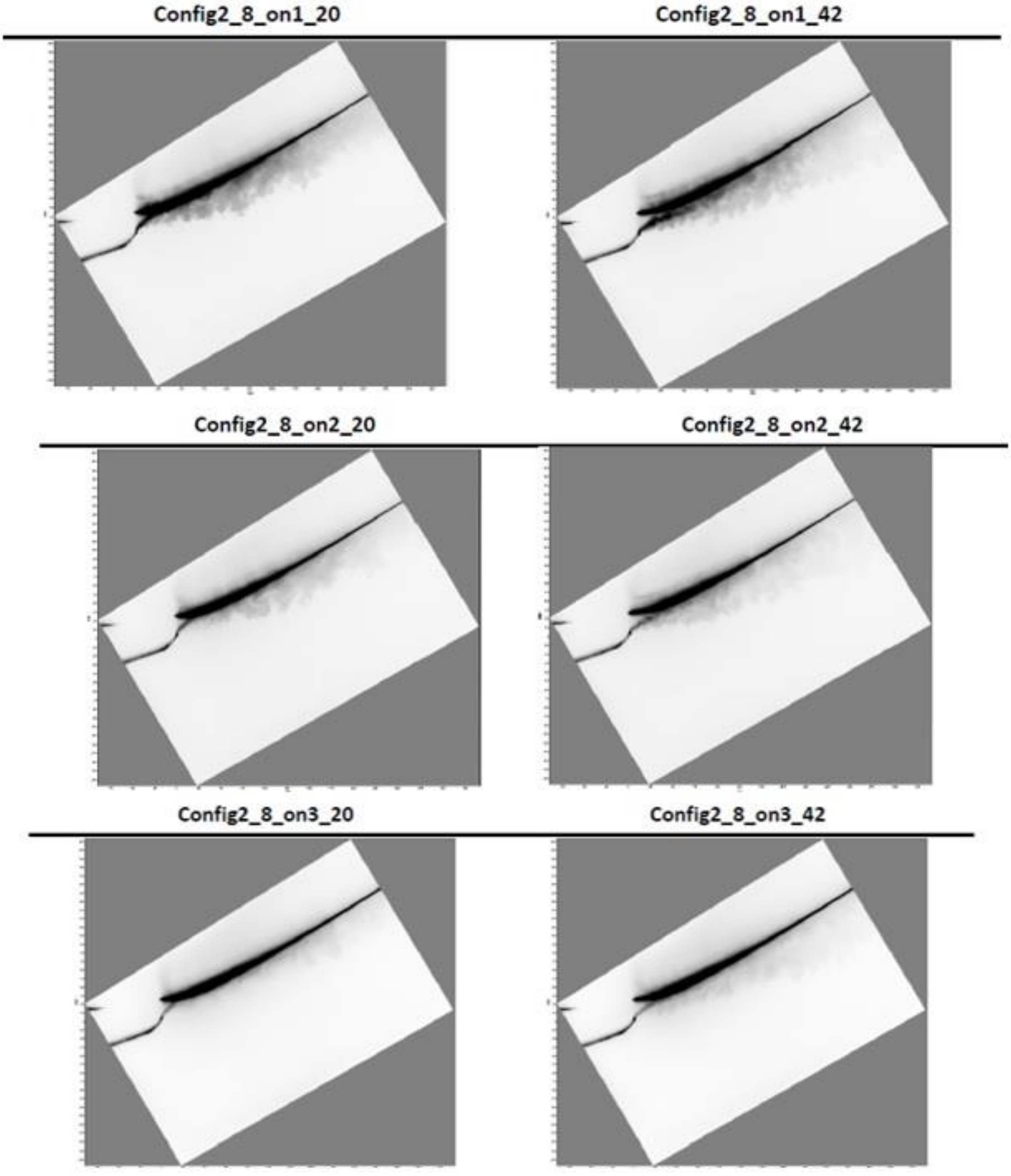

Figure 6 – Smoke visualization with flap=20°, different pressure ratios and free stream speed =20 m/s (left) and 42,5 m/s (right), at an angle of attack=8°

The smaller the freestream speed, the smaller is the deflection deviation of the jet from its blowing duct exit direction and the higher is the increase in total lift in terms of percentage with respect to the No Blow conditions at the same speed.

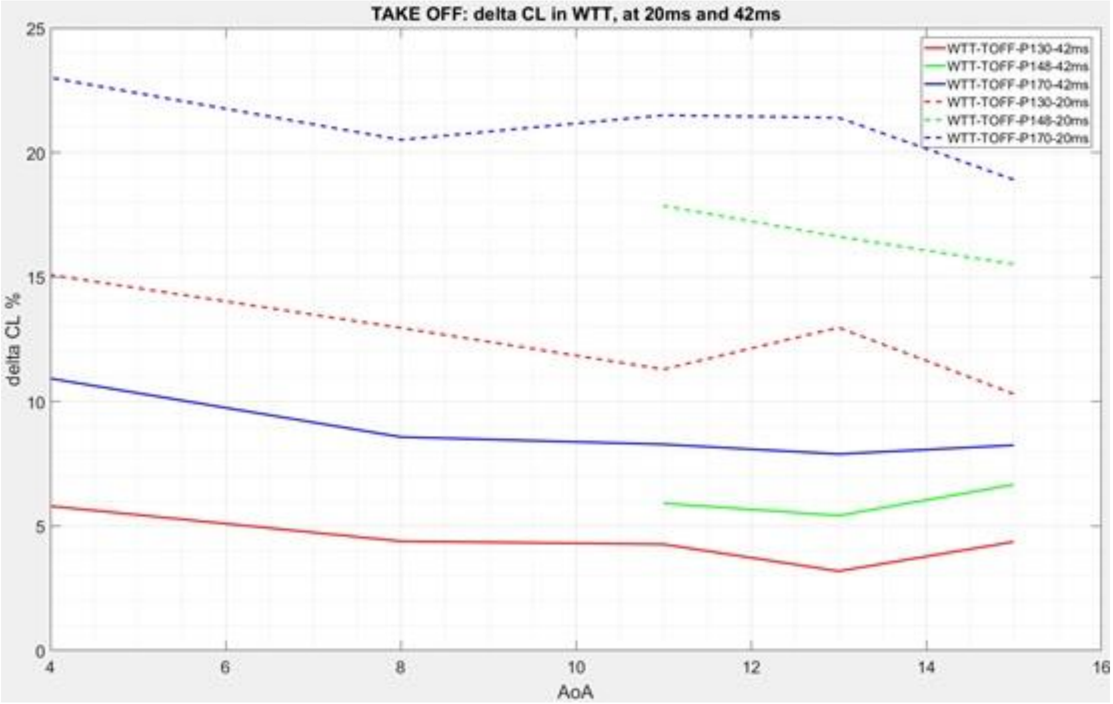

Figure 7 – Take-off configuration, WTT, delta CL% trend at different pressure ratios and free stream speed= 20 and 42.5 m/s

In fact, the blowing jet acts as a change in curvature of the main airfoil: the less is the jet deflection deviation, the higher the main airfoil curvature experienced by the flow, the higher the suctions and so the higher the gain in lift.
CFD simulations, done for Pressure ratio=1.48 and different free stream speeds, but flap=15°, reveal the same behavior, thus proving the blowing jet mechanism also for different flap deflections.

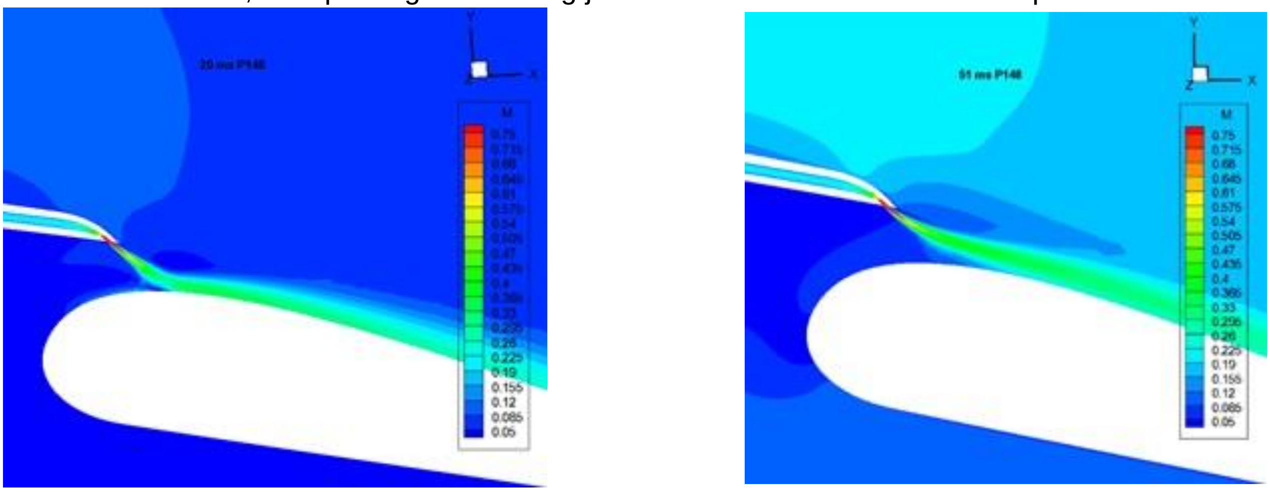

Figure 8 – CFD 2D flap=15°, effect on jet deflection of the free stream speed: 20 m/s (left) vs 51 m/s (right) at pressure ratio=1.48

Thus, it appears clear that the smaller the free stream speed, the higher is the gain in lift. By the way, it has to be considered that to substantiate the performance gain on the aircraft a suitable free stream speed should be used, identified as the design one for the SAT aircraft: smaller speed are useful to understand the jet effectiveness mechanism, but they are meaningless from a performance point of view. On the opposite, the above evidence underlines a possible blowing piping redesign, letting the flow exit more deflected downward, to enhance the increase in curvature.
Focusing back on the aircraft performance, the free stream chosen as the design one for take-off is 51 m/s, which is the one used in the CFD simulation during the design phase.

These results will be from now on compared to the WTT results at their maximum free stream speed, chosen to be 42,5 m/s to avoid as much as possible the blockage, even if VKI L1-A maximum speed is 60 m/s.
Comparing the resulting WTT deltaCL % with those from CFD simulations:

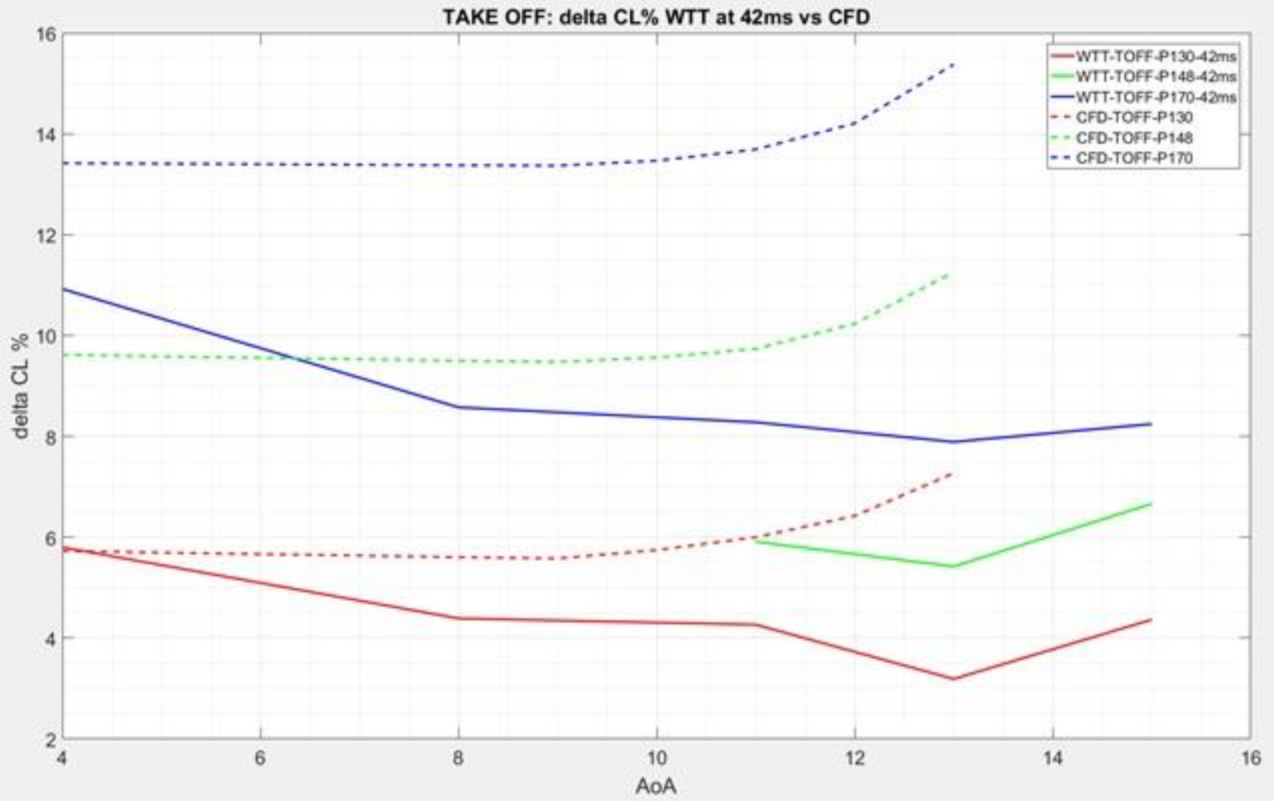

Figure 9 – Take-off configuration, delta CL% WTT at 42.5 m/s vs CFD at 51 m/s, different pressure ratios

In this case it is possible to see that delta CL% from CFD are always higher than those from WTT at 42.5 m/s.
Some considerations should be done:

- CFD simulations are at 51 m/s. It was the established analysis speed before the testing WT selection and it refers to a feasible take-off speed for SAT. Consequently, with respect to WTT, ran at a smaller speed, the CFD delta CL% should be smaller, exactly because of the change in deflection of the blown jet, as also proven by Fig.6 and Fig.7.
- The gap in delta CL between CFD at 51 m/s and WTT at 42,5m/s increases as the pressure ratio increases
- CFD delta CL tends to increase going up with incidence, whilst instead from WTT this delta CL tends to decrease by increasing the angle of attack, at all the test speeds.

The facts that for WTT:

- delta CL tends to decrease with AoA increasing
- delta CL at 42,5 m/s is smaller than CFD at 51 m/s
- the difference between CFD and WTT at 42,5 m/s increases with increasing the pressure ratio

can be explained through WT blockage, which is the phenomenon through which the wind tunnel flow develops differently than in free air.
Moreover, the larger the model, the larger are the pressure wave, the larger is the space needed by the isobars to be fully developed: if constrained between walls, the air cannot fully expand or compress. This fact can be seen observed the compacted isobars as below (Fig. 10). Moreover, WTT flow accelerates because of the interaction between model and endplates, the delta CL is therefore penalized in the wind tunnel with respect to CFD simulations.

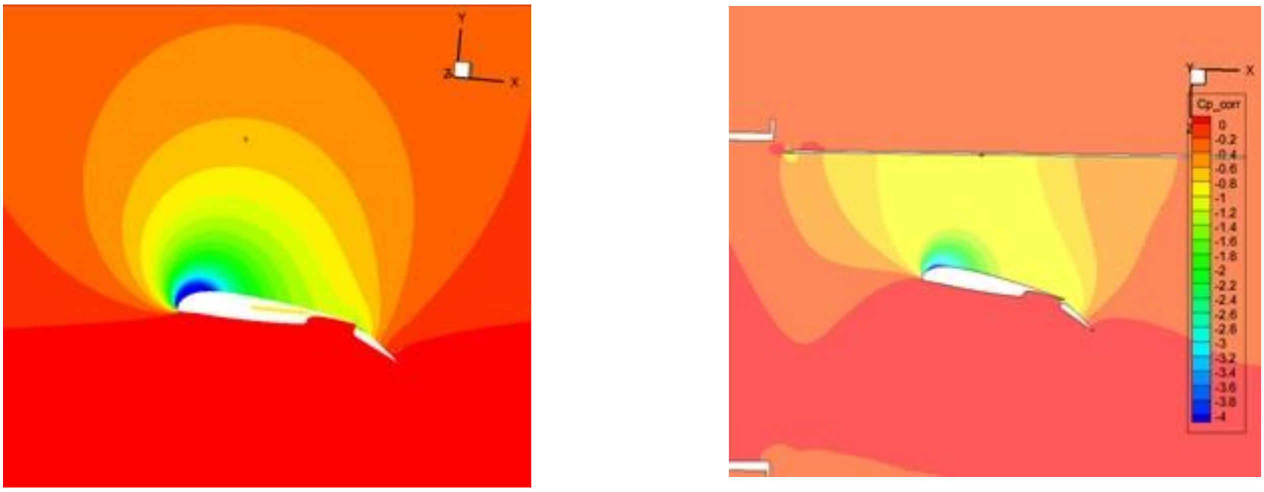

Figure 10 – Different isobar development between free air and WT specimen, for the same condition

The same behavior can be observed by increasing pressure ratio: the more the pressure ratio is increased, the more the suction on the main airfoil should be higher, the more the developing flow needs space, which is not available in WTT, thus the less is the resulting effect.
Another clue of how blockage is influencing the tests, is the CLα slope in No Blow conditions.

	CFD	WTT 20m/s	WTT 30m/s	WTT 35m/s	WTT 40m/s	WTT 42m/s
CLα [1/deg]	0.1105	0.0778	0.07955	0.08015	0.0807	0.07655
delta (wrt CFD)	-	-29.6%	-28.0%	-27.5%	-27.0%	-30.7%

Table 3 – CLα comparison, in No Blow conditions, between CFD and WTT at the different speeds

CLα in WTT is always smaller than CFD.
Moreover, looking carefully at the complete CL-alpha curves in No blow conditions:

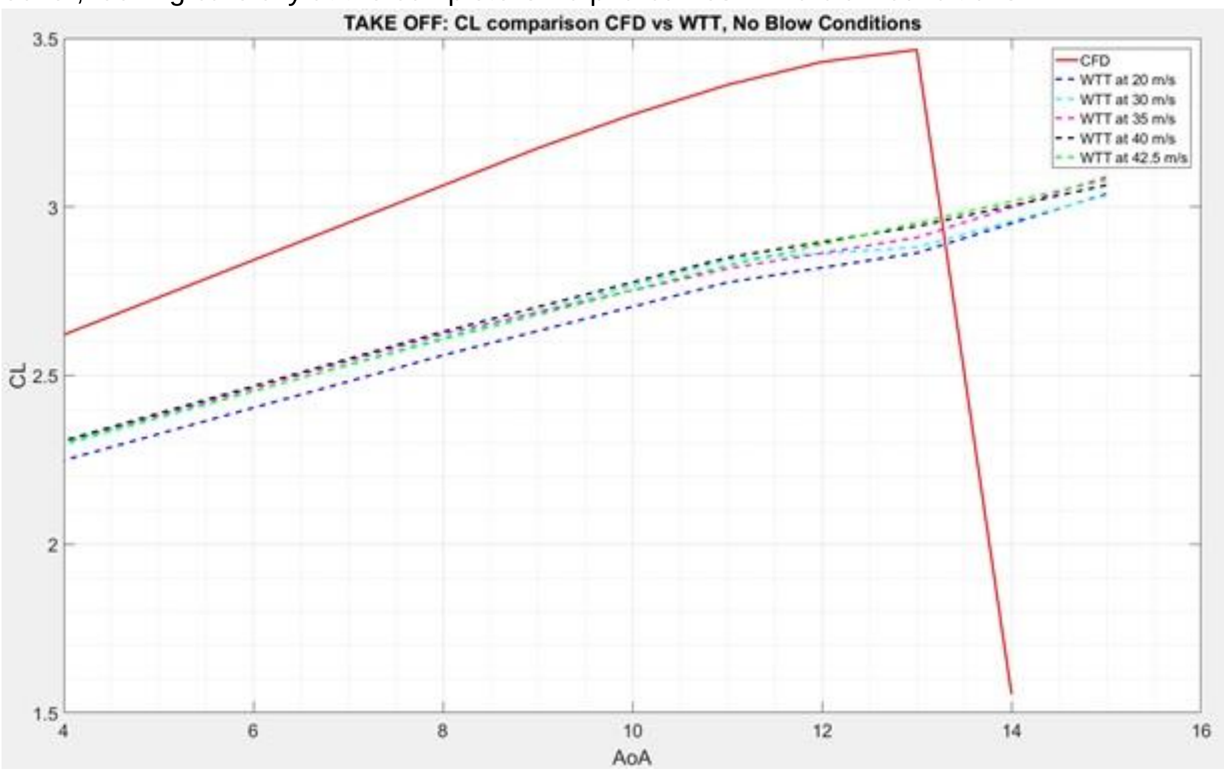

Figure 11 – Take-off configuration, CL comparison CFD vs WTT, no blow conditions

It is possible to see that CFD results have always a higher CL value.

The correct simulation of the stall angle of attack is a well-known challenge for CFD, but in this specific case no stall is visible in WTT. Due to the blockage, which generates smaller pressure gradient in the test chamber, WTT results in a much higher value of stall angle of attack with respect to the model in free air.
Both CLα and absolute CL values, at the different WT speeds, indicates how blockage is influencing results, already in No Blow conditions: the WTT-based values should be carefully considered, but still the tests are useful to explain physics phenomena and trends.
Nevertheless, it should be underlined that, for this project, the MOTHIF specimen cannot be reduced. The dimensions were constrained by the main airfoil trailing edge. It had to contain both blowing ducts system and pressure taps routing for measurements. To do so, the trailing edge has been manufactured in SLS ALM, but the smaller dimension was limited by both constraint of manufacturing capabilities (considering also ensured quality) and costs. Therefore, a smaller specimen, to reduce blockage effect, was not possible.
Moving to the comparison of delta drag with respect to No Blow Condition:

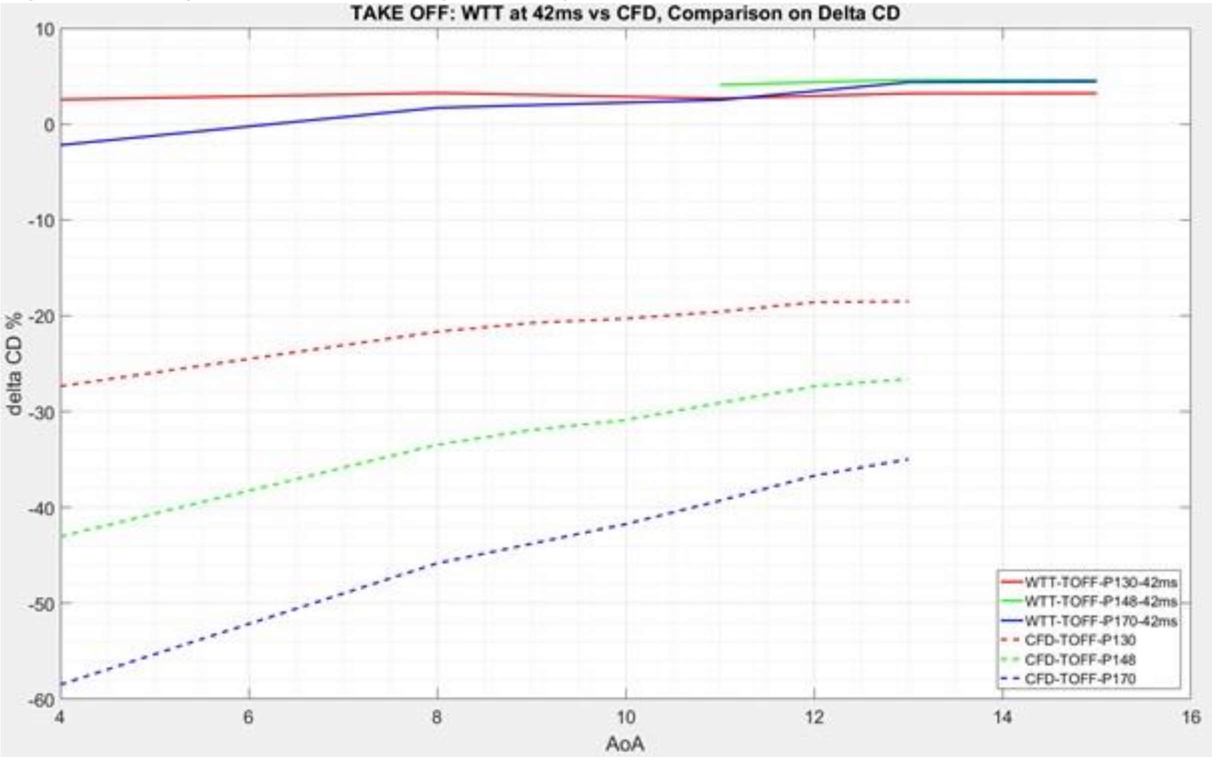

Figure 12 – Take-off configuration, delta CD WTT at 42.5 m/s vs CFD, different pressure ratios

In Fig. 12 it is possible to see that, even if from Fig.9 delta CL % values are more comparable between CFD and WTT at 42.5 m/s, the delta CD% for the same speed is no more comparable.
In particular, in WTT, it seems that the drag increases by increasing pressure ratio; moreover delta CD % behavior in WTT is much less sensitive to pressure ratio, if compared to CFD data.
This behavior may be explained by the following considerations:

- by increasing the pressure ratio, the skin friction increases.
- by increasing the pressure ratio, the suction increases all over the main airfoil. In particular, this increase in CFD is visible also on the airfoil nose, which is also the airfoil zone in which, at each condition, the suction is higher. Thanks to the particular nose droop configuration, negative pressure acts also towards the drag direction, by reducing it. So, having a nose suction increase, means having a drag reduction. By the way, it has been seen that in WTT the CL increase at 42,5 m/s, considered as homologous speed for the 51 m/s CFD test case, is not as expected. On the opposite, the delta CL% increase is more pronounced at 20 m/s and indeed for that WTT also the drag is reduced (Fig.13).

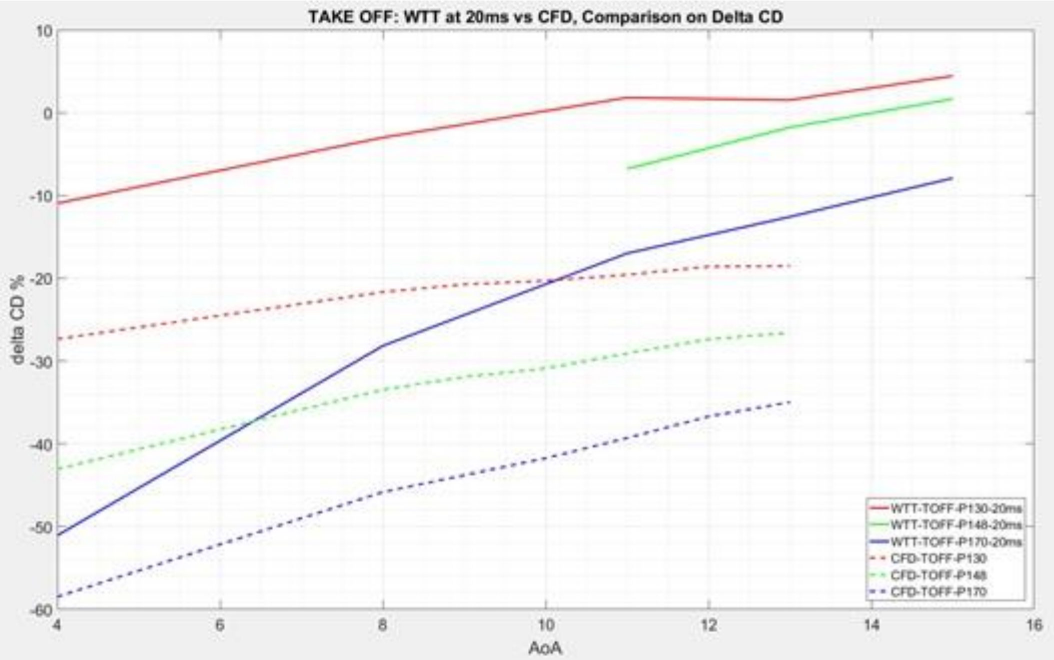

Figure 13 – Take-off configuration, delta CD WTT at 20 m/s vs CFD, different pressure ratios

So,blockage, having a huge effect on lift gaining, also influences drag reduction. The main effect seems to be on nose suction.
Looking now deeply to delta Cm:

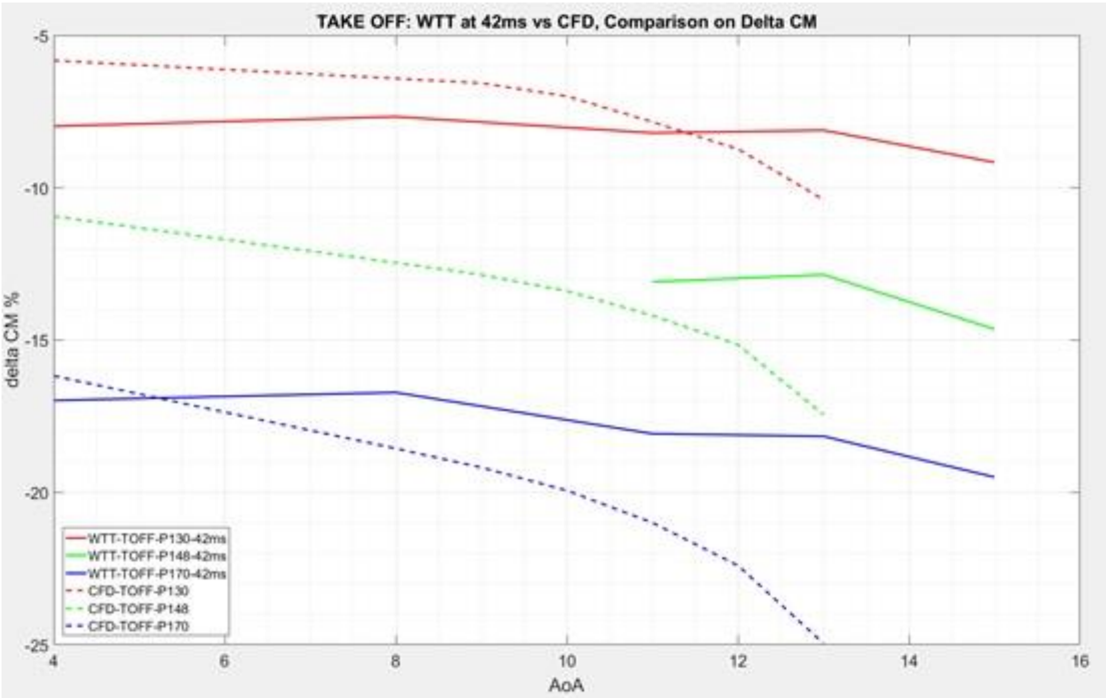

Figure 14 – Take-off configuration, delta Cm% WTT at 42.5 m/s vs CFD, different pressure ratios

From Fig.14 it is possible to see that at 42,5 m/s WTT delta Cm is more comparable with CFD with respect to the delta CL (Fig.9).
This means that the loss on the lift gaining on the main airfoil is not a simple homothetic scaling of the Cp distribution.
To better appreciate what happens it is convenient to look at the pressure distribution and compare again CFD and WTT at 42,5 m/s.

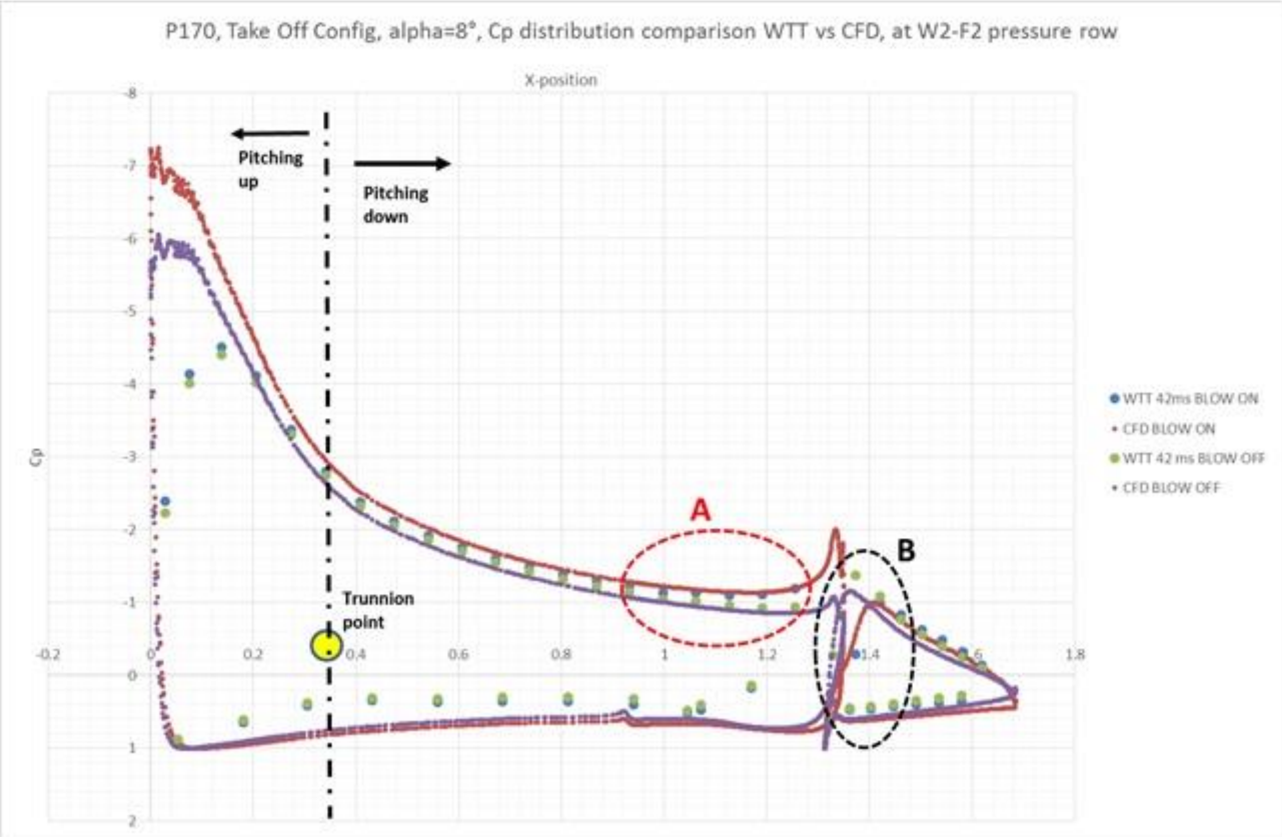

Figure 15 – Take-off configuration, Cp distribution comparison between CFD and WTT at 42,5 m/s, pressure ratio=1.7 and No Blow, alpha=8°

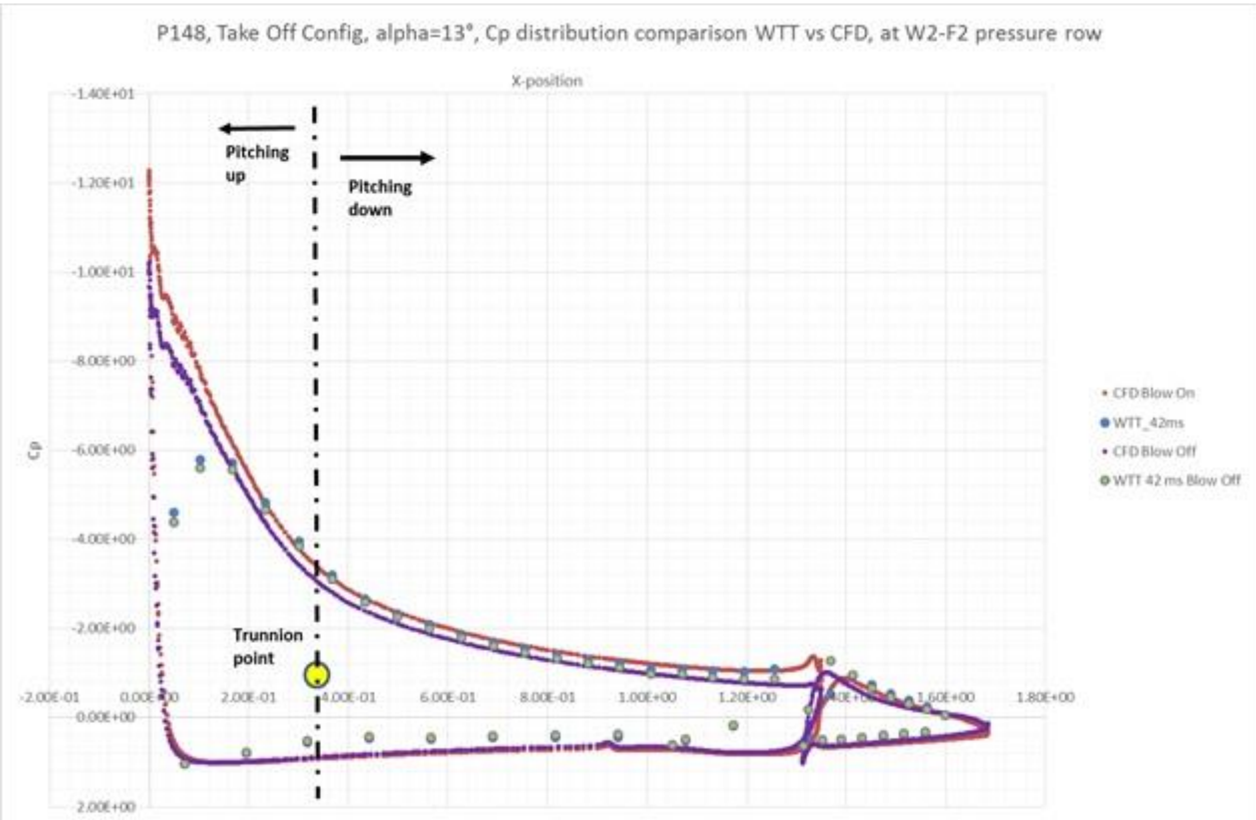

Figure 16 – Take-off configuration, Cp distribution comparison between CFD and WTT at 42,5 m/s, pressure ratio=1.48 and No Blow, alpha=13°

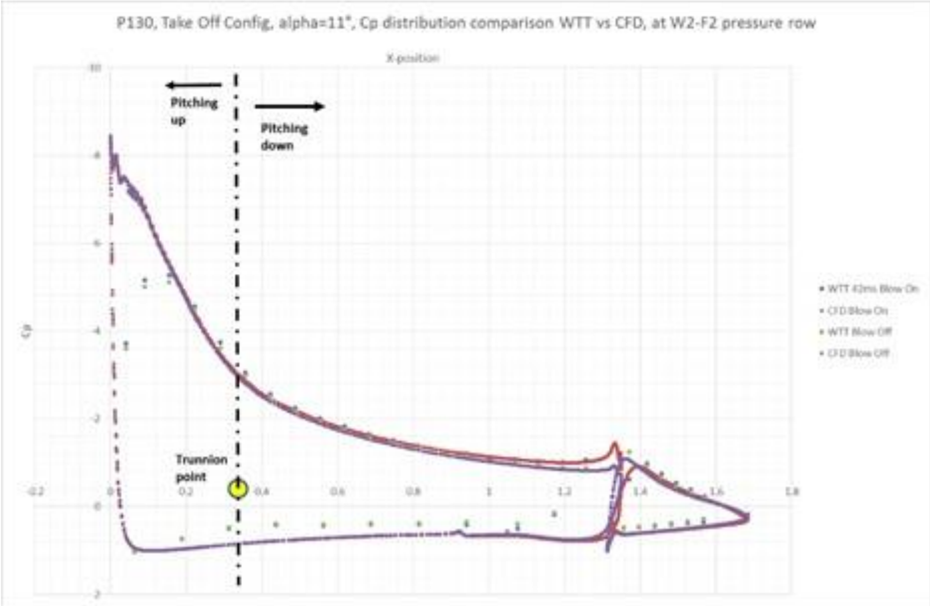

Figure 17 – Take-off configuration, Cp distribution comparison between CFD and WTT both at 42,5 m/s, pressure ratio=1.3 and No Blow, alpha=11°

To explain the differences in the delta Cm and delta CL between WTT and CFD, some specific points will be here below deeply investigated, starting from Fig.15.
The difference in delta CL, between WTT at 42,5 m/s and CFD, is 4%.
The difference, for the same points, but regarding delta Cm, is 1%.
It means that the increase in negative Cm between WTT and CFD is more similar than the gain in CL.
This cannot be explained by a simple homothetic translation of the Cp distribution.
Figure 15 shows the comparison of the Cp distribution along the chord on the same spanwise position (relative to W2-F2 (model centerline) pressure tap rows position) between CFD and WTT, between Blow Off and PR=1.7.
In the picture it is possible to see CFD P170 blow on (red circles) and CFD blow off (violet circles); also, it is possible to see WTT P170 blow on (blue circles) and WTT blow off (green circles). The considered angle of attack is alpha=8°.
From Fig.15 several things may be pointed out:

- Absolute values of suction for CFD are always higher (both Blow On and Blow Off) than WTT. In fact, the absolute value of CL is always higher for the CFD simulation, already in No Blow condition. This another clue of the blockage effect.
- The gain in suction in CFD is more constant along the chord, with a sudden slight increase at the main trailing edge: this is the effect of the blown jet, which acts all over the airfoil.
- In particular, looking at the CFD Cp distribution (red and violet) it is possible to appreciate a slight rearward movement of the stagnation point of the airfoil. This rearward movement makes the suction greater on the nose but it is not enough to explain also the suction gains all along the chord: this is more related to the jet dragging effect on the main airfoil boundary layer, especially on the trailing side.
- The gain in suction in WTT is smaller than the one from CFD and it is not constant chordwise. It is possible to see a bit of increased suction on the nose, but not comparable to the gain from CFD: this explain also the reduced effect of the jet on drag, since nose suction contrasts the drag. Then, as visible in "circle A", the suction in WTT gets greater (but still smaller than CFD) at the main airfoil trailing edge, just next to the blown jet
- The resulting reduced gap in delta Cm, between WTT and CFD, is exactly because in WTT the increased suction is more evident on the main airfoil trailing edge, so in a zone in which the arm with the trunnion point is higher and the effect on the negative pitching moment higher too.

- As visible from the "circle B", both WTT and CFD show a lift deterioration on the flap when blowing is on. In particular, it is possible to see that Cp on the flap nose drops when the blowing is activated. This is exactly the effect of the jet impingement. Cp distribution on the flap looks very similar between CFD and WTT, both in blow off and on conditions, thus resulting in less sensitivity to WT blockage
- WTT stagnation point positioning seems to be very close to the CFD one: this means that the WT is not downwashing the specimen with respect to the given rotation. This also means that the cut-off on the negative pressure for the WT specimen is not related to a change in the angle of attack, but more related to endplate positioning, as previously explained.
- Looking at the CFD Cp distribution, the maximum suction point is higher in value and more forward with respect to the WTT. This is due to the floor and roof endplates, which both distorts the isobar, which should need more space in free air to be fully developed. Also, a rearward relocation of the maximum suction point is visible. The rearward relocation of the maximum suction point depends on the interaction between floor endplate and airfoil suction side, causing a Venturi tube: in this tube throat, the maximum speed is reached, so the maximum suction. And this is a pure wall-effect

All the above considerations are valid for the other points in Fig.15-17.

9. Landing Configuration Results (Flap=30°)

Starting analyzing landing configuration (i.e. flap=30°) results:

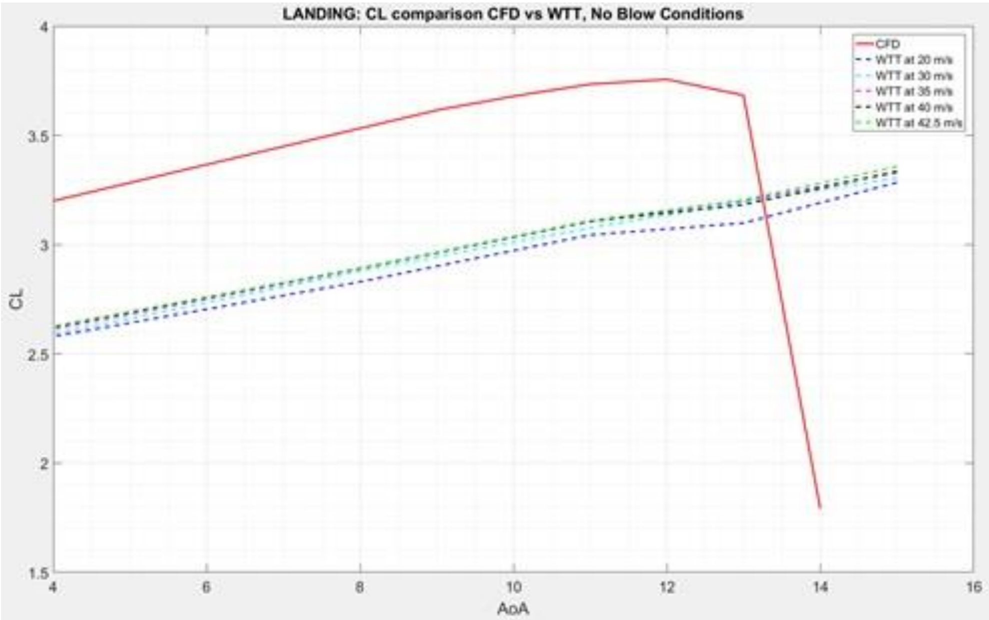

Figure 18- CL-α curve in landing configuration, no blow, CFD vs WT at different free stream speeds

	CFD	WTT 20m/s	WTT 30m/s	WTT 35m/s	WTT 40m/s	WTT 42.5m/s
CLα [1/deg]	0.083	0.0626	0.071875	0.069025	0.067175	0.066475
delta		-24.6%	-13.4%	-16.8%	-19.1%	-19.9%

Table 4 - CLα slope in landing configuration, No Blow, CFD vs WT at different free stream speeds

It is possible to see that, as for take-off configuration, CFD CL curve in no blow condition is always higher than WTT, at every free stream speed.

As for the previous flap configuration, also the CLα slope for the WTT is always smaller than CFD simulation results.

As already visible from the Take Off configuration analysis, it is not yet possible to distinguish a stall angle of attack. Again, as reported for the Take Off case in the previous paragraph, this is due to blockage. In WTT, having a smaller lift and smaller suction on the airfoil nose, at every angle of attack, means to have a smaller adverse pressure gradient on the trailing edge. So, it results in an increased capability to reach a higher angle of attack, which by the way is not proper of the wind tunnel specimen, but it is due to the interaction between WT specimen and WT test chamber arrangement, as for the following considerations:

- In free air CFD results in higher CL and higher values of suction on the airfoil nose;
- In the wind tunnel, with its arrangement, at the same flap configuration and angle of attack, the CL is smaller and also the suction on the airfoil nose is lower;
- As seen in Fig.15, it is not the stagnation point to be changed by WT test chamber wall arrangement, but the suction magnitude and maximum suction point position;
- As stated in [1], CFD simulations of the wind tunnel arrangement with the specimen, gives back the results of WTT with a very good agreement: this state the CFD capability prediction and its accuracy, at least on the linear part of the lift curve
- This means that the differences in CLα slope, in CL absolute values and the explanations already given are substantiated by means of CFD analysis, having clear the CFD reliability of predicting performance in No Blow condition also in the wind tunnel.

Looking at the delta CL:

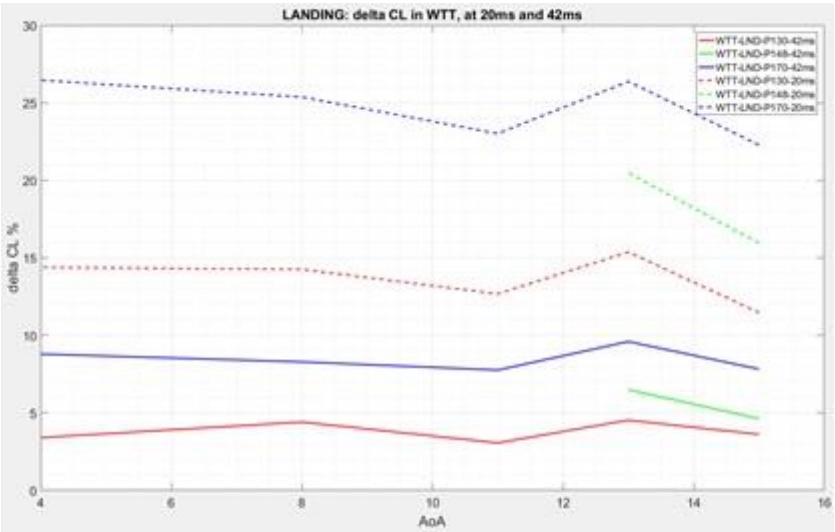

Figure 19 - delta CL in landing configuration, different pressure ratios, WTT 20 m/s (dashed line) vs 42.5 m/s (full line)

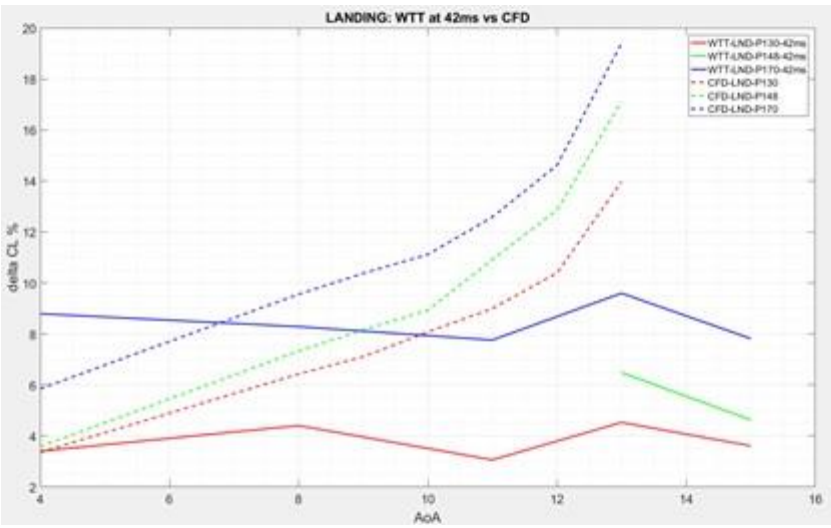

Figure 20 - delta CL in landing configuration, different pressure ratios, CFD (dashed lined) vs WTT at 42.5 m/s (full line)

As for the take-off configuration, at 20 m/s delta CL in WTT are higher than CFD, whilst WTT at 42,5m/s delta CL is more similar to CFD ones. This can be seen by comparing Fig. 19 and Fig.20.
Looking at Fig. 21, for every pressure ratio, from CFD simulations the delta CL grows as the incidence. In WTT, instead, increasing the angle of attack the delta CL remains more or less flat, for each pressure ratio.
This WTT behavior is the same for both the limit speeds.
Moreover, it is visible also in take-off configuration.
In addition, for CFD simulation, the delta CL% increase with respect to the angle of attack increases faster with the angle of attack for landing than for take-off configuration.

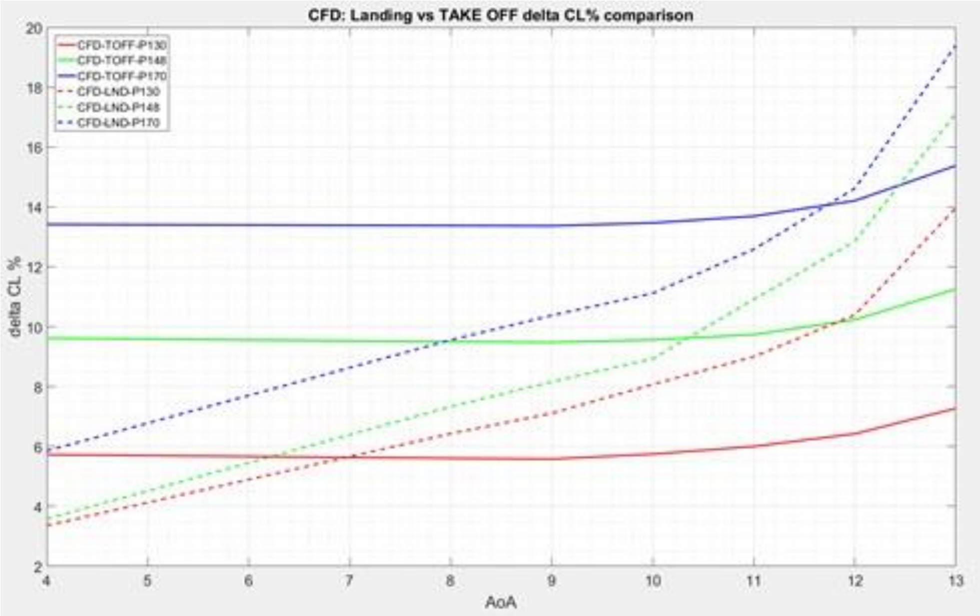

Figure 21 - CFD: landing vs take-off delta CL% comparison

While instead, in WTT, comparing delta CL between landing and take-off configuration at the same WTT speed:

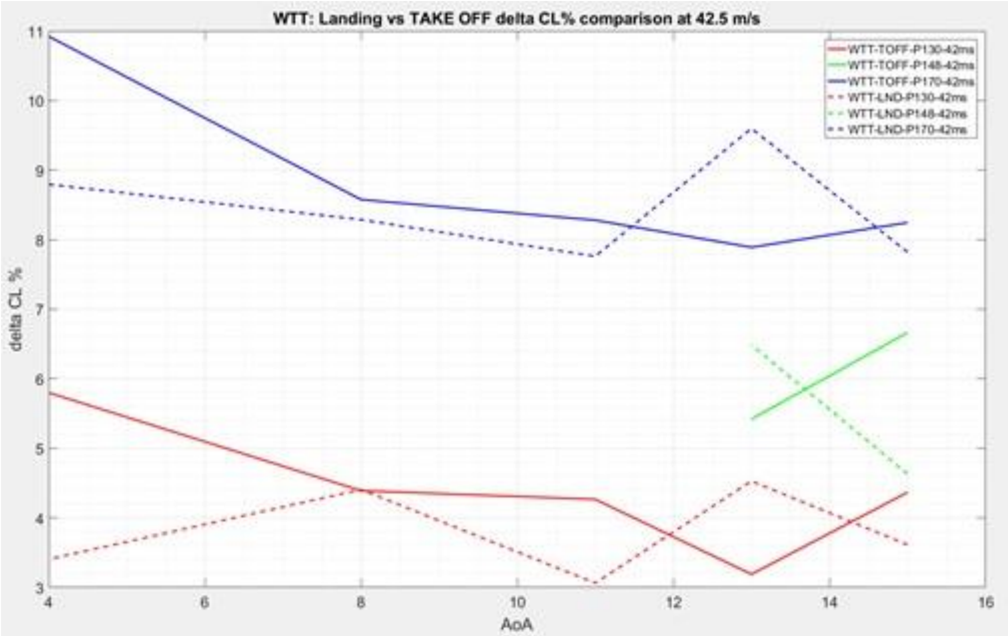

Figure 22 - WTT: landing vs take-off delta CL% comparison at 42.5m/s

From Fig.21, it is visible from CFD simulation a change of delta CL value and behavior between take-off and landing. Instead, from Fig.22, it is possible to see that in the wind tunnel, at identical speed and pressure ratio, take-off and landing configuration delta CL looks very similar, both on the behavior with respect to the angle of attack and on the absolute values.
This could be explained through the blockage, which jeopardizes the effects and their dependencies.
Considering the delta drag in terms of percentage:

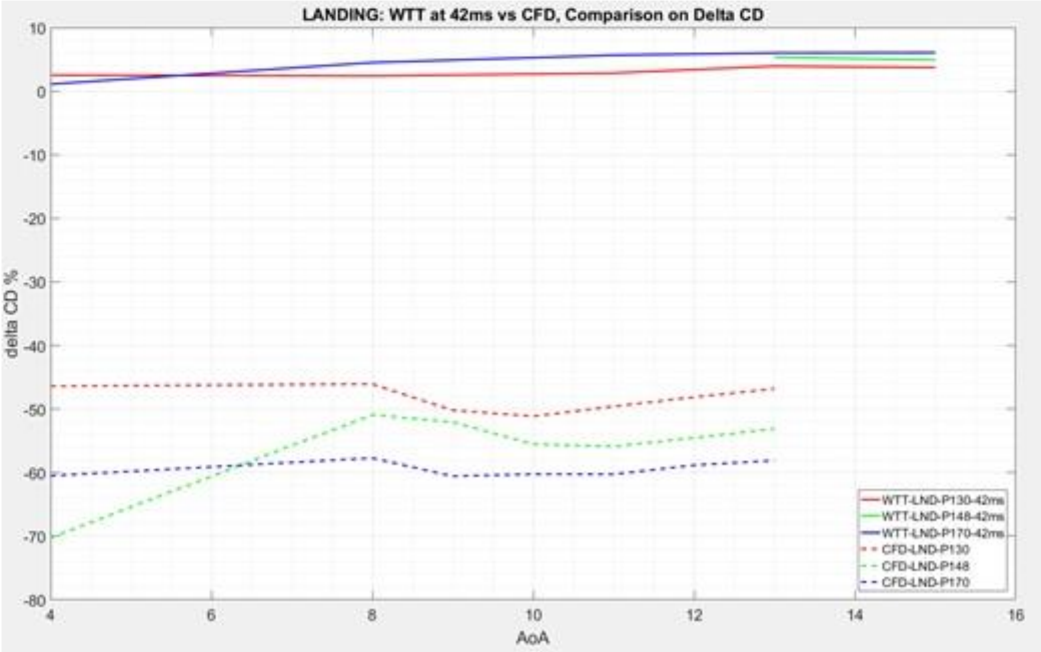

Figure 23 - delta CD in landing configuration, different pressure ratios, CFD vs WTT at 42.5 m/s

Regarding instead the Cm:

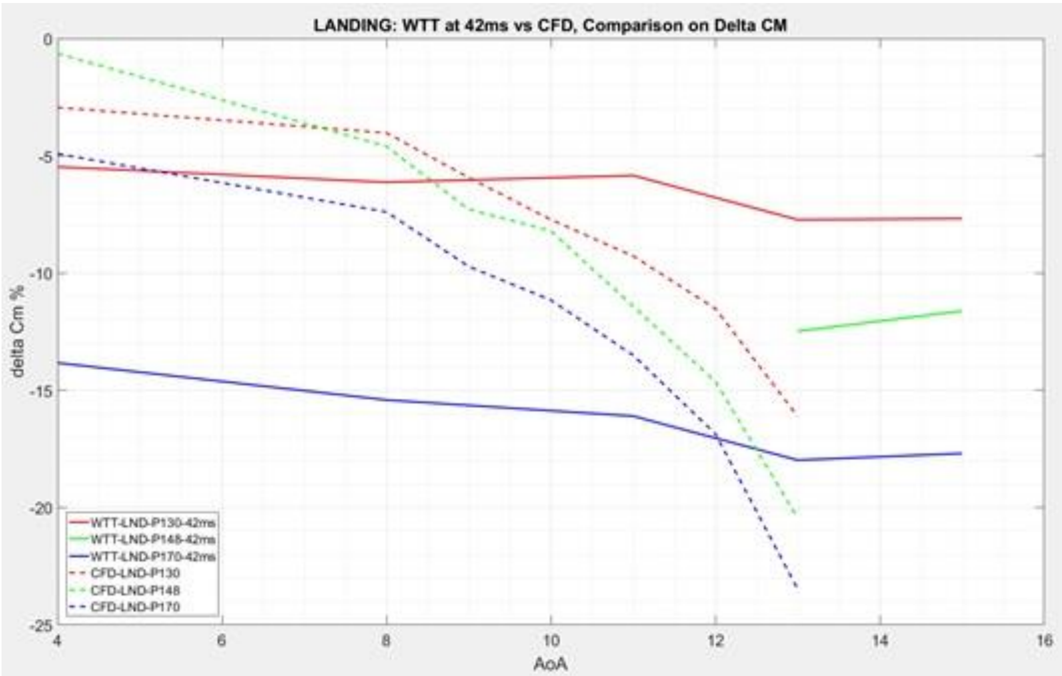

Figure 24 -delta Cm in landing configuration, different pressure ratios, CFD vs WTT at 42 m/s

Also looking at the deltaCm behavior, it is possible to see its flatness with respect to the angle of attack: blockage is jeopardizing the effect of CL and pitching moment increase.

10. Considerations on WTT Results

WTT shows two-dimensionality of the flow, as proven by the pressure distributions on the three different pressure probe rows, at a different angle of attack, pressure ratio and wind tunnel speed. This was a target of the WTT and it has been respected.
WTT results are strongly affected by blockage effect, mostly related to the specimen cross-section dimension with respect to the wind tunnel test chamber, as proven by CFD [1].
Specimen cross-section is forced by the constraint of quality and manufacturing cost, in particular for the capability to manufacture a representative blowing duct system in the main airfoil trailing edge, together with the pressure probes routing.
WTT has been done at different free stream speeds: 20 m/s is the smaller, 42.5 m/s the higher one.
The smaller the free stream speed, the higher is the effect of the blown jet, at each pressure ratio, in increasing lift capabilities.
Design phase CFD simulations in free air condition have been done at 51 m/s, which is a representative operative take-off speed for the aircraft.
Delta coefficient between CFD and WTT are more comparable with experimental free stream speed at 42.5 m/s.
The blockage effect limits the flow natural development in terms of pressure, thus jeopardizing the effect on maximum suction and its position.
CL absolute values are smaller than expected, while the pitching moment absolute value is higher, since the maximum suction positioning is moved more rearward. Furthermore, stall is not clearly visible and CL max is longer delayed.
From pressure distribution comparison with free air CFD simulation, it is possible to appreciate that:

- the geometric angle of attack is well taken but the surface pressure changes in terms of suction values and distribution: this is the blockage effect.
- the flap pressure distribution and aerodynamic coefficients are in better agreement with simulations: thus flap, for its geometric dimension, is less sensitive to blockage.

The blowing jet effects in terms of CL increase, drag reduction and negative pitching increase are visible and comparable with CFD free air expected results, even if the jet effect is slightly jeopardized by the blockage.
By the way, WTT confirms the gains and the behavior in blowing conditions, as expected during the design phase, but deeper substantiating the effects also at different free stream speeds, giving a useful insight on the physics of the blowing jet.
In particular, WTT:

- Confirms the super-circulation activation on the main airfoil
- Confirms the increase in suction, on the whole main airfoil suction side, with a sudden increase at main airfoil the trailing edge
- Confirms the increase in negative pitching moment, due to the main airfoil trailing edge side suction increase
- Confirms the drag reduction due to main trailing edge blowing
- Confirms the flap lift worsens when the blowing jet is activated
- Highlight the connection between free stream speed and blowing jet effectiveness

Furthermore, as for [1], the comparison of WTT experimental results with CFD wind tunnel simulation makes possible a substantiation of the CFD reliability, giving consistency on the expected outcomes and performance benefits obtained during the design phase.

11. Conclusions

Thanks to the support of European funding, Piaggio developed a blown flap system which has been wind tunnel tested within the MOTHIF project in collaboration with VKI and SONACA.
Experimental results from WTT at VKI, confirms the gains in lift and the physic mechanism behind the lift augmentation: a supercirculation is activated by the main airfoil trailing edge blown flow, which

increases the suctions on the main airfoil, from the nose to its trailing side, with a higher effectiveness on the latter. This supercirculation, since it energizes the boundary layer on the trailing side of the main airfoil, so increasing its mean speed, makes also the maximum incidence to be increased, thus letting the airfoil to sustain more adverse pressure gradients.
The same blown jet impinges the flap nose, thus reducing its suction and consequently lowering the flap lift capabilities.
The effects of the increased suction on the main airfoil gets higher when, even alternatively, the blown flow exit speed increases or the free stream speed decreases:

- in the first case, the blown flow exit speed depends on the pressure ratio between reservoir and ambient pressure: increasing this ratio, the blown flow exits speed increases. Pressure ratio= 1.88 is the limit to obtain nearly sonic exit conditions. WTT maximum pressure ratio has been 1.7, which corresponds to M=0.9 at the diffusor exit.
- In the second case, as the free stream speed is reduced, the jet exits more parallel to the diffusor geometry direction, increasing the curvature of the main airfoil, thus leading to higher suction and higher lift gain

The effects of reduced lift on the flap, instead, decreases by increasing pressure ratio, so increasing the blown jet exit speed.
The pitching moment gets more negative, since the suction increases, especially on the main airfoil trailing side.
The drag instead is reduced: this is more visible at smaller free stream and smaller flap deflection from WTT, while instead it is always present in CFD simulations. The CD reduction is mainly due to:

- The increased main airfoil suction: since the particular nose droop design of the airfoil the suctions acts, more than usual, not only in the lift direction but also on the drag one, by reducing it
- The presence of the jet itself, acting as a thrust

Overall the reduction effect is more visible on CFD, while instead in WTT, where suction is jeopardized because of the blockage, the reduction is lowered and at high free-stream speed the CD on the contrary increases.
The blockage has been the main issue regarding the wind tunnel tests: this aspect may not be reduced since it depends on the ratio between specimen and test chamber cross-section. The specimen dimensions have been instead constrained because of manufacturing cost and quality, since the allocation of all the internal piping (pressure probes and blowing system) within the main airfoil trailing part.
Blockage influences:

- The lift absolute values, reducing them with respect to free air expected ones
- The maximum incidence and the stall, which is not yet visible from the WTT
- The CLα lift slope, reducing it
- The gains when the blowing system is activated, through two aspects:
  - by jeopardizing the effect with respect to the incidence, which results quite constant instead of being growing as for free air simulations
  - by reducing the percentage gain over the no blow condition with respect to free air simulations
- The gain in drag is more emphasized:
  - at higher pressure ratio than free CFD simulations
  - at smaller free stream speed
  - at smaller flap deflection (more visible in take-off configuration than for landing)

Exactly the fact that smaller speeds and less deflected configurations lead to a more emphasized drag reduction are clues of the effect of blockage.
Although these high blockage effects, which strongly affects the absolute values of lift obtained during the WTT, the comparison with CFD simulations concerning the experimental setup itself (see [1])

enabled the correlation between CFD and experimental activities, thus giving consistency to the expected gain in free air of the system obtained and foreseen during the design phase.
This result is very important, tracing the path for an innovative design methodology, in which CFD and WTT are used together to obtain more comprehensive results in a faster and cheaper way, by overcoming their respective limits.
The next step could be the test of the same specimen in a bigger wind tunnel test chamber, for giving consistency to the results and the blockage effects discussion.
Moreover, having understood the importance of the blowing jet deflection with respect to the mean aerodynamic chord, it is worthwhile to redesign the blowing duct, to obtain, at the same reference speed of 51 m/s, a more downward blowing jet (as for smaller free stream in WTT), so increasing the gain in the lift.
Furthermore, a higher pressure ratio, leading the blowing jet to sonic conditions, should be studied but taking particular attention to sonic and expansion wave reflection between main airfoil trailing edge and flap.

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Data Availability Statement

Data that support the findings of this study are available from the corresponding authors upon reasonable request.

Disclaimer

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