A parametric study of a thick, incompressible flow over a curved surface

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Abstract: *The purpose of this paper is to investigate the lift phenomenon produced by the Coanda effect when a fluid flows over a curved surface. A secondary goal was to quantify and to integrate it on super circulation wing aircraft configurations. Therefore we have conducted a series of CFD studies, varying the fluid velocity and measuring the pressure gradient over the super circulated curved ramp. The results showed that thick jets provide the anticipated lift force which is proportional to the flow velocity. Although in this case the ratio between the Coanda lift and the thrust of the jet itself is less than 10% on average. The immediate interpretation is that, by using thick jets we can increase the lift generated by the SCW aircraft bearing in mind that the main lift is not generated by this effect but rather by diversion of the jet downwards.*

Key Words: *Coanda effect, CFD, Menter SST, super circulation*

1. INTRODUCTION

Super Circulation Wing (SCW) aircraft have been in use since the 1970's. Because of their innate ability to obtain higher lift, this aircraft architecture has been one of the favorite for large STOL transport aircraft. Early attempts to theorize the lift generated by the fan flow over the top of the wing are given in Refs [1] through [4].

It is apparent that the Upper Surface Blown (USB) technology current state of the art does not benefit from the special aerodynamic lift obtainable by the Coanda effect but rather relies on both delaying the stall of the super circulated wing section and diverting the fan flow downwards. Although it is clear that those are the main contributors to the USB STOL characteristics, it is still worth to investigate whether or not the principles of Henri Coanda's *lenticular aerodyne* of the 1930's, Ref [5] could be applied to increase the lift capabilities of such aircraft.

In predicting the lift of a USB wing both experimental Ref [6] and computational fluid dynamics [7] have been used. Current efforts are made in simulating thin jets of air, i.e. 5% of the ramp span, over curved surfaces mainly for applications on flapless aircraft. However, this paper will focus on the CFD study of thick flows in obtaining the Coanda effect lift. References [8] and [9] provide comparative studies of CFD and experimental data showing different performances of viscosity models. Although there are different viscosity models that yield satisfactory results, we will adopt Menter's k-omega Shear Stress Transport (SST) which is described in detail in Refs. [10] and [11].

Upper Surface Blown wing aircraft have been studied and manufactured since the 1970's by both western and eastern designers. However different the individual model may be, the main features remain quite similar. Apart from the boundary layer control mechanisms described in Ref [12] and [13], the wing top is designed to be essentially flat. Also the flap system, as shown in Ref [14] and [15] is slot-less and has a smooth, curved top in order to direct the fan flow downwards using the Coanda effect.

The flying principles of the lenticular aerodyne relied however on a different principle, i.e. by passing a tangential flow of fluid over a curved surface we not only divert the flow but also obtain a down pressure.

The magnitude of this down pressure is proportional to the velocity of the fluid but also dependent on its temperature Ref [1]. Hence, the current study tries to analyze how to integrate this effect in order to increase the lift obtained by USB wings.

Reference [1] defines the momentum coefficient, Eq. 1, that describes the additional lift provided by the USB wing. However, Ref [2] proves that this coefficient is, at times, inferior to the experimental data, indicating that the momentum coefficient does not account for the full phenomenon.

$$C_{\mu} = \frac{\dot{m} \cdot U_{jet}}{q} \tag{1}$$

where

C_{μ} is the momentum coefficient

q is the dynamic pressure of the free stream

c is the chord length

$\dot{m}$ is the mass flow

U_{jet} is the injector velocity

2. THE CFD SETUP

Modeling the Coanda effect is a difficult task, especially over curved surfaces, mainly Because of the centrifugal effects that are inherent and the turbulence production near the wall. References [8] and [9] indicate that the k-epsilon viscosity model generates too much turbulence in the boundary layer –hence failing to predict boundary layer separation. Another turbulence model considered is the classic Wilcox k-omega which is more successful in predicting boundary layer separation, being however inferior to the k-epsilon in the far field region.

The viscosity model used in this study has been Menter’s k-omega Shear Stress Transport, which blends in the k-omega model near the wall and emulates the k-epsilon in the far field. The SST variation is even more useful in this case since the flow follows a curved path.

The two dimensional computational domain was chosen such that the pressure outlets will have a minimal impact on the simulation. Due to the limited resources, the flow exiting the ramp will inevitably cross one of the boundaries; however the boundary effect is minimized by placing the limits as far back as possible.

Jet thickness was chosen to be higher in regard with the curvature radius and arc span than the one traditionally used in order to imitate the proportions of a turbofan engine to the wing. The injector height was 20% of the curvature radius.

The mesh is based on paved triangles which are more refined near the injector and the curved ramp region and coarser near the pressure outlets. Figure 1 depicts the whole mesh and detailed views of the injector and ramp.

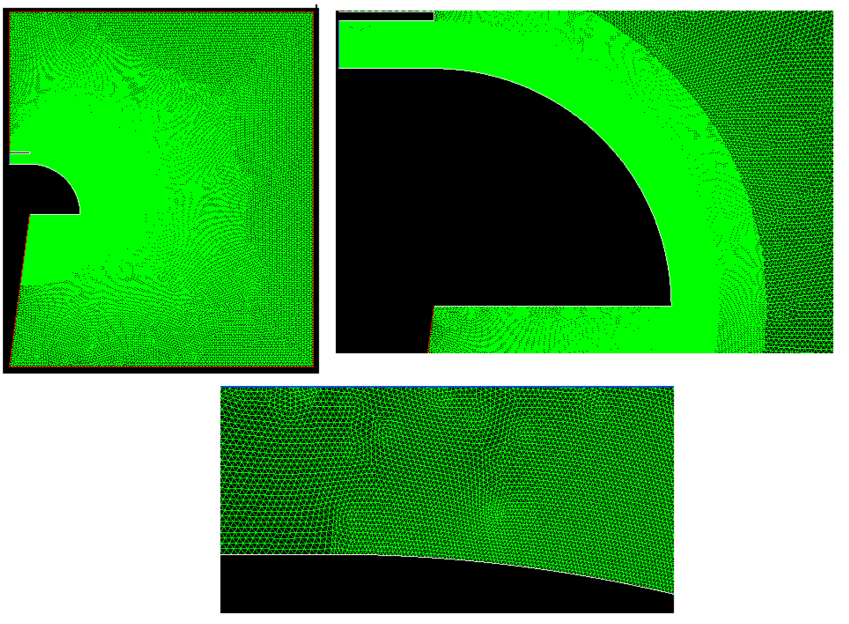

Fig. 1 The computational mesh used for the CFD simulations

Figure 2 presents a comparative study between various turbulence models tested during preparation of the velocity parametric study.

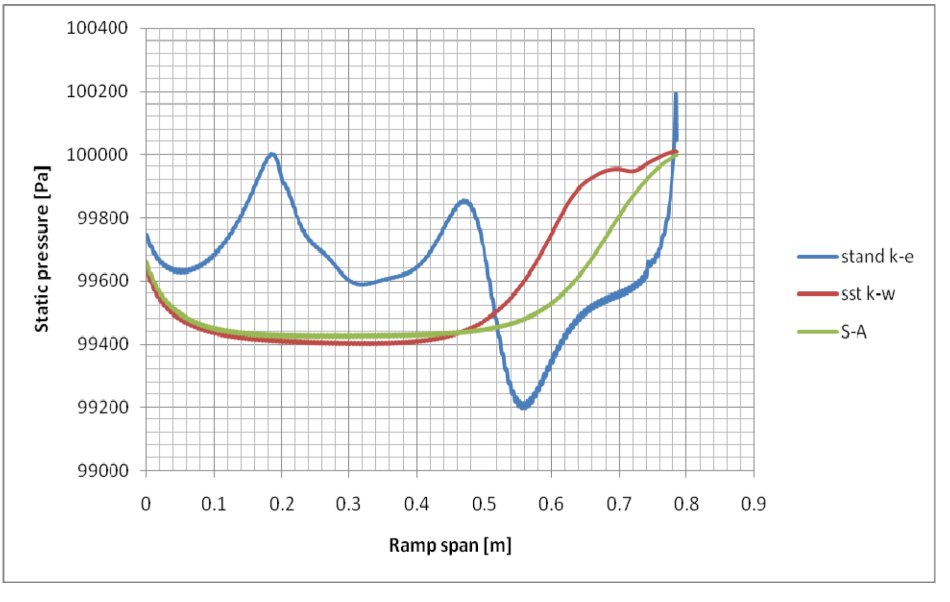

Fig. 2 The static pressure across the super circulated ramp calculated by various viscosity models at 50m/s

The turbulence models tested were:

1. The k-epsilon standard model predicted the splitting of the injected flow immediately after the contact with the ramp. Across the ramp span, the pressure dropped as a result of the secondary jet that attached itself to the ramp. Figure 3 shows a velocity plot of the case.

Although this model was expected to predict an attached flow due to the turbulence production near the wall, the result was surprising yet not entirely contradictory.

2. The Spallart-Almaras one equation model showed results very similar to the ones obtained with the SST k –omega model except the crucial matter of predicting the fluid separation at high velocities. It also predicted a smaller pressure drop than the k-omega SST.

3. Menter's SST k-omega was the model that not only converged more rapidly but also predicted boundary layer separation at high velocities. The model was also indicated by the quoted literature as the best for simulating flows over curved walls.

As velocity is the key parameter that dictates the down pressure obtained by Coanda effect over a curved ramp, a parametric study was conducted. The decreases in pressure obtained are plotted in Fig.4. A maximum velocity was chosen such that the flow would be incompressible in order to better simulate the fully developed secondary flow of the turbofan engines.

In order to evaluate the effectiveness of the lift by Coanda effect the lift obtained was compared to the jet thrust. Equations 2 and 3 were used in calculating the lift of the curved ramp and injector thrust respectively.

$$T = \rho \cdot A_{inj} \cdot U_{jet}^2 = \dot{m} \cdot U_{jet} \tag{2}$$

where:

ρ is the density of the fluid used (air) which is a constant for the incompressible velocities tested here

A_{inj} is the aria of the injector section

$$F = \Delta \overline{p} \cdot A_{ramp} \tag{3}$$

where:

$\Delta \overline{p}$ is the mean pressure drop across the ramp span

A_{ramp} is the aria of the super circulated ramp

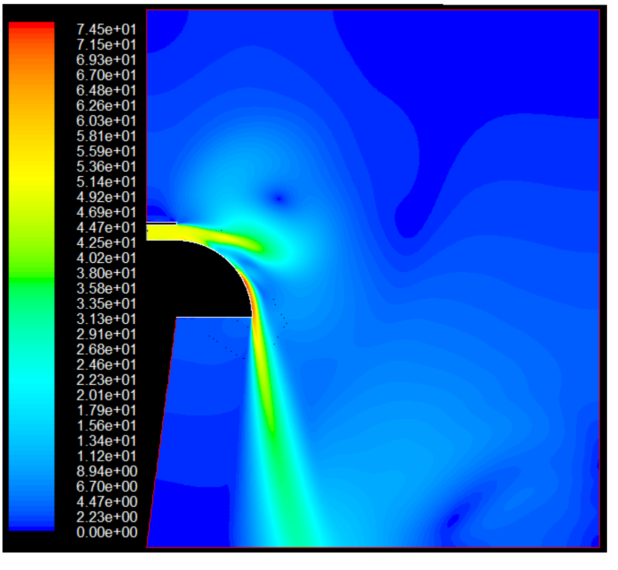

Fig. 3 The velocity contours of the k-epsilon super circulation prediction

Figures 5 and 6 show the magnitude of the two entities versus the exhaust velocity from the injector. A first remark is that, at least for this jet thickness, the ramp provides a greatly inferior lift in comparison to the thrust provided by the injector, i.e. it is much more convenient to direct the jet flow downwards than to seek lift by the Coanda effect over curved surfaces. However this does not mean that the lift generated by the ramp should be discarded. By adding it to the lift already obtained by the current USB aircraft one can expect a predicted 16% to 6% increase in lift, depending on the exhaust velocity of the fan. In Figs. 7 and 8 contour plots are presented for velocity and pressure magnitude, respectively.

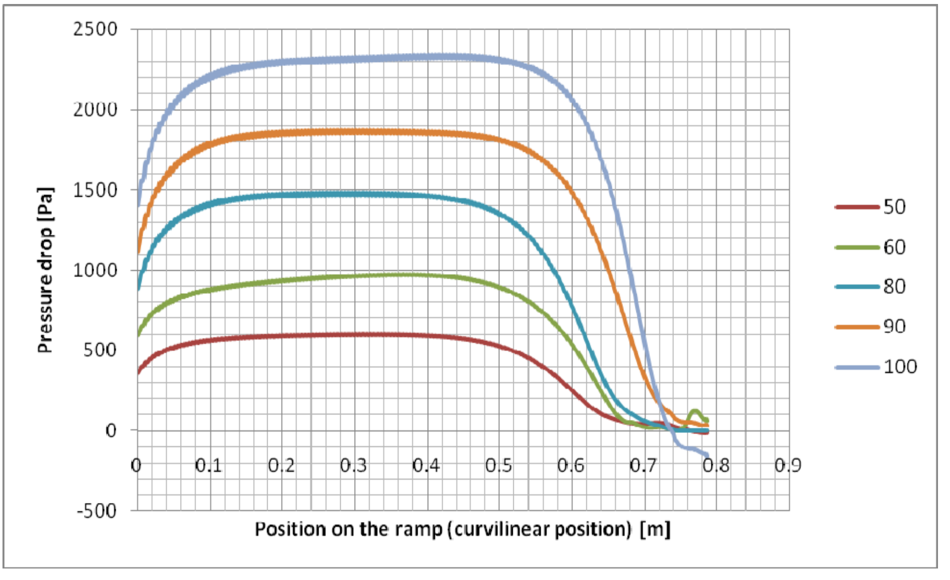

Fig. 4 The pressure drop across the ramp for various fluid velocities

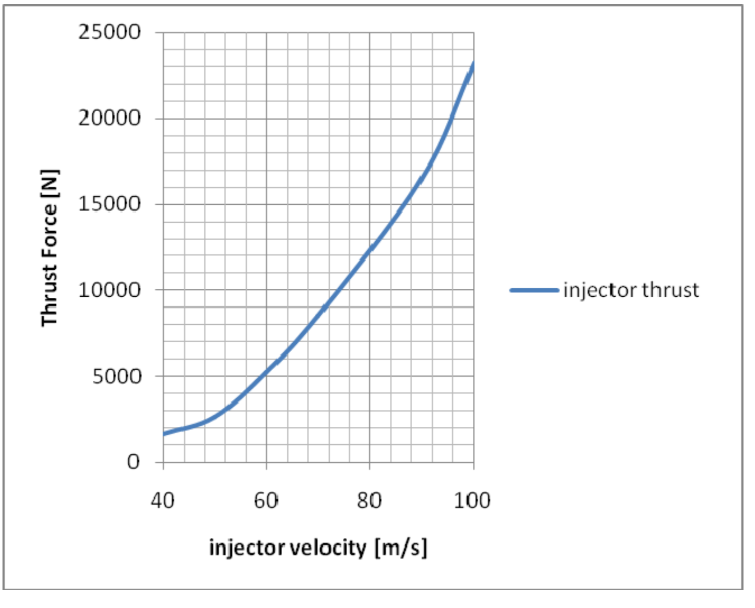

Fig. 5 Thrust of the jet versus fluid velocity

Although the super circulated ramp lift is higher as the exhaust velocities are higher, it needs to be pointed out that the ramp lift to injector thrust ratio decreases from an estimated 16% at 40 m/s to almost 9% at 100 m/s.

Based on the findings a proposed solution has been devised in order to integrate the super circulation lift obtained from a curved surface into the already familiar USB configuration. Figure 9 shows an embodiment of this solution.

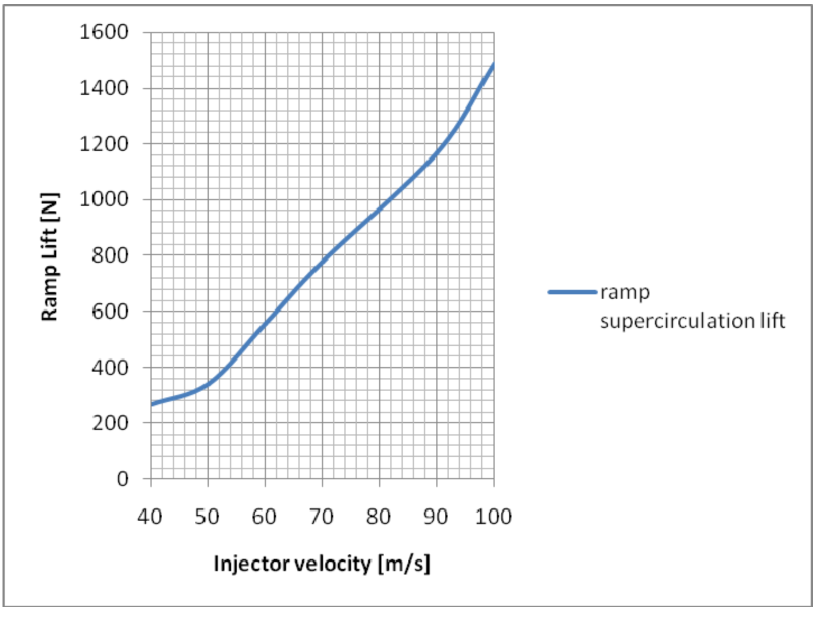

Fig. 6 The lift obtained from super circulation of the ramp versus velocity

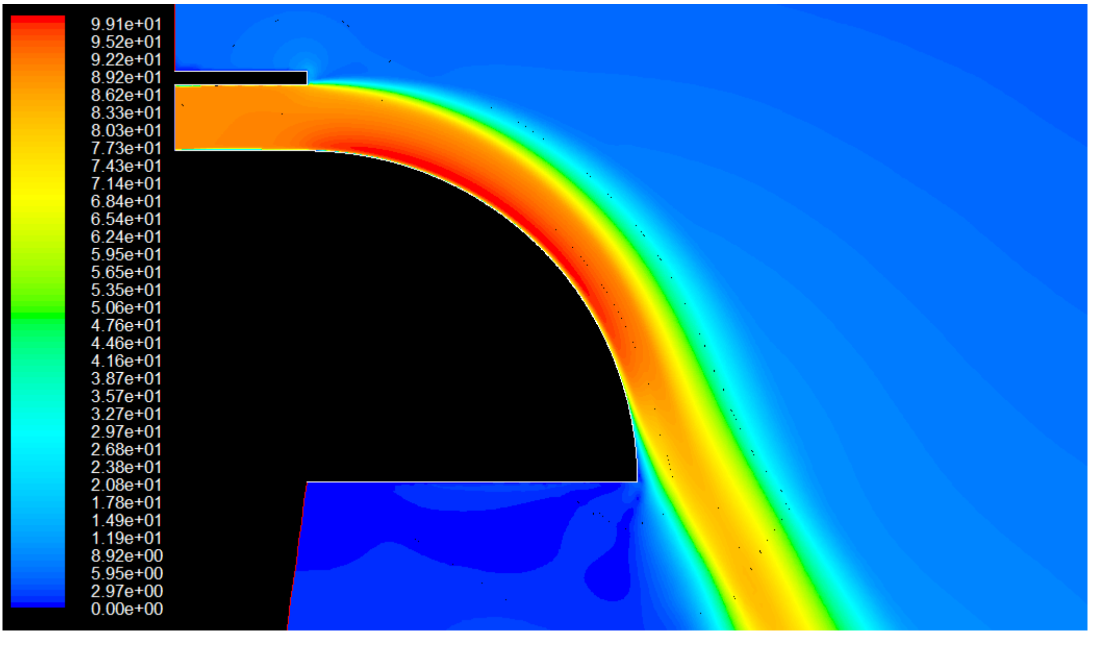

Fig. 7 Velocity plot near the ramp

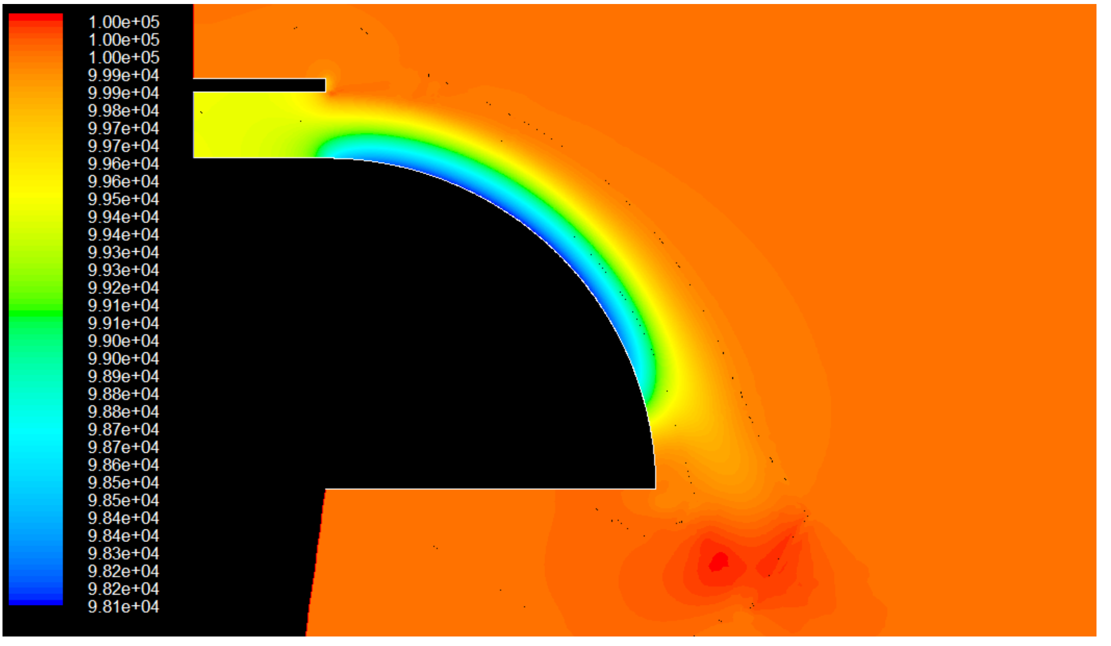

Fig. 8 Pressure plot near the ramp at 90 m/s

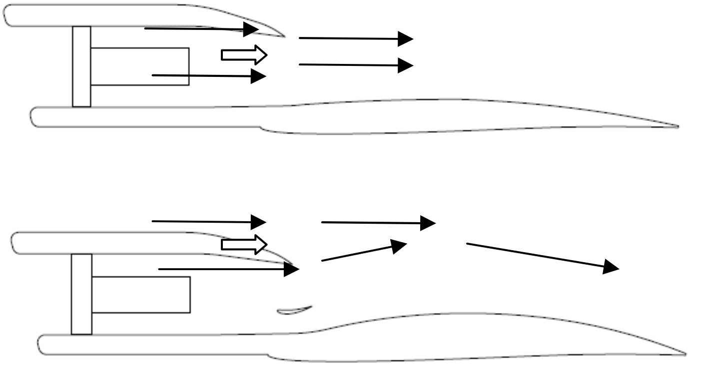

Fig. 9 Conventional SCW (up) and proposed integration of the curved ramp for a SCW aircraft (down)

3. CONCLUSIONS

Based on the known state of the art of super circulation wing aircraft and on the lift phenomenon that arises from the Coanda effect over a curved surface, a parametric CFD study has been conducted in order to estimate the possible benefits of combining the two.

The tests were conducted using a Reynolds Averaged Navier-Stokes pressure based solver, for sub-sonic incompressible flows of unheated air.

The viscosity model chosen was Menter's k-omega SST which was selected based on the available literature which compared various models with experimental data. Additional comparisons were made with three other viscosity models.

Although further computational and experimental study is needed in order to validate the magnitude of the predicted increase in lift, the following findings can be formulated:

1. The lift dependency to flow velocity over a constant radius curved wall is found to be largely linear, having a steep positive slope.
2. The lift obtained by a jet of 20% thickness - as a percentage of the ramp curve radius- used to super circulate a curved ramp at an incompressible regime is approximately 10 times smaller than the thrust of the jet used for the super circulation.
3. Super circulation lift, in this case, varies with the injected fluid velocity between 16% at 50 m/s and 6.4% at 100 m/s as a percentage of the jet thrust.
4. The fluid appears to accelerate while attached to the curved ramp in a region of about 10 % of the jet thickness, although it must be pointed out that the region does not include the boundary layer.
5. Curved ramps can be integrated in super circulation wing designs, particularly USB configurations in order to increase the total lift.

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