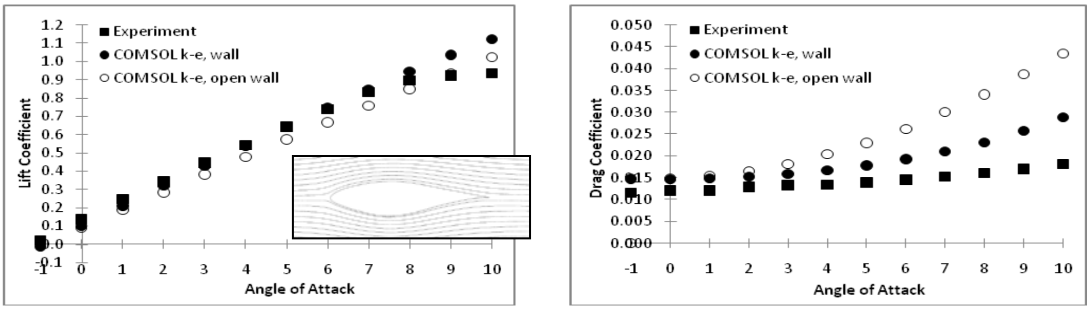
The results exhibited in both examples above serve to indicate, that the computational procedure and choice of turbulence model seem to be satisfactory, and could lend support to further use of the approach in the numerical parametric study.

All computations in the present study were performed on a laptop computer with a 2.10 GHz Intel Core Duo processor, 4 GB of RAM, and 32-bit Operating System. Typical computation time for the computation of the flow characteristics around a two dimensional airfoil is in the order of 4 hours with around 300,000 degrees of freedom by using stationary segregated solver in $k-\varepsilon$ turbulent model analysis.



(a) *(b)*

Figure 8. Comparison for validation of S809 airfoil of CFD computational results using COMSOL™ 4.2. k-e turbulence model and experimental values from Somers (NREL [51]) at Re = 1E6 (a) Lift coefficient (b) Drag coefficient

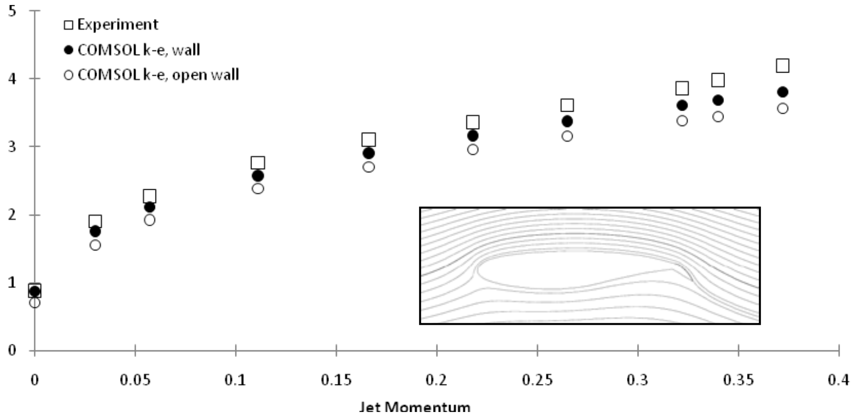


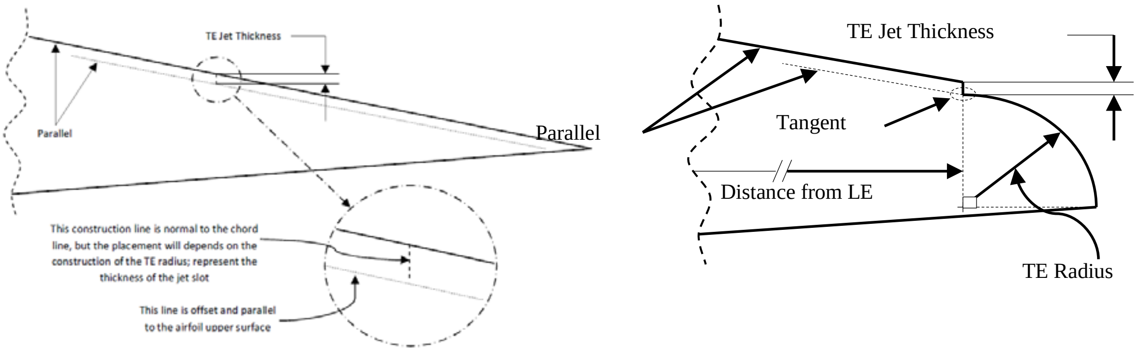
Figure 9. Comparison of lift-curve slope for GTRI Dual Radius CCW airfoil with LE blowing on CFD computation using COMSOL™ 4.2. k-e turbulence model and experimental values from Englar et al [13] at Re = 395,000

Results and Discussions

Coandă Jet Design Configuration

For the purpose of assessing the influence and the effectiveness of the Coandă enhanced lift on wind-turbine blade, a generic two-dimensional study is carried out. The problem at issue is how the Coandă jet can be introduced at the trailing edge of the airfoil, bearing in mind that such design may recover any losses due to the possible inception of flow separation there. In addition, for effective Coandă jet performance, a curvature should be introduced.

Furthermore, the thickness of the Coandă jet as introduced on the airfoil surface could have a very critical effect on the intended lift enhancement function. For best effect, the lower surface near the trailing edge should be flat, as suggested by Tongchitpakdee [18-19]. The design of the Coandă-configured trailing edge should also consider the off-design conditions. With all these considerations, a configuration suggested is exhibited in Figure 10. This figure illustrates the initial airfoil shape in the vicinity of the trailing edge, and the final airfoil shape there. With the pressure distributions for all cases obtained by running COMSOLE ® CFD code. The iteration process required the geometry to be remeshed and a new CFD solution to be obtained.



(a) (b)

Figure 10. Trailing edge construction of the Coandă configured airfoil (the jet flow is tangential to the rounded circular sector) (a) initial configuration (b) final configuration

S809 Airfoil Computational Results

Next, we would like to investigate the influence of specifically designed airfoil geometry for wind turbine application, and for this purpose a typical S809, in clean and Coandă jet equipped configurations. S809 airfoil represents one of a new series of airfoils which are specifically designed for HAWT applications [25-27]. For the present study, the numerical simulation was carried out at two free-stream velocities. These are 5.77m/s (corresponding to Re = 3.95 x 10^5) and 14.6 m/sec (corresponding to Re = 1 x 10^6), which represent low and high free-stream cases, respectively, while the chord-length is maintained at c = 1m, and density at ρ = 1.225 kg/m^3. The baseline for assessing the advantages of Coandă jet from parametric study on S809 airfoil is the computational result for the clean airfoil. The computational result for this baseline case has been validated by comparison of the computational value for the same S809 airfoil to the experimental results based on wind-tunnel test.

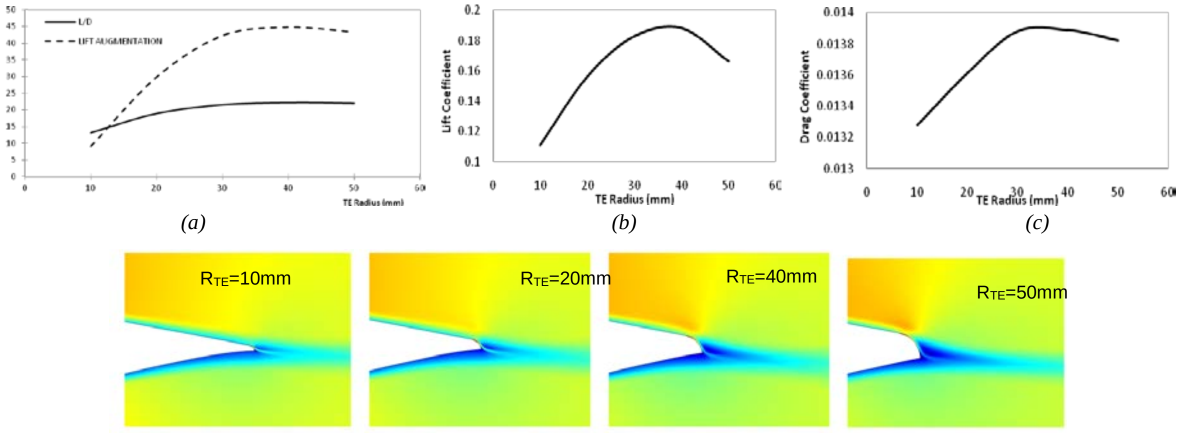
The two-dimensional numerical simulation study for the S809 airfoil is carried out in logical and progressive steps. First, the numerical computation is performed on the clean S809 airfoil, then on the Coandă jet configured S809 airfoil without the jet (i.e. after appropriate modification due to TE rounding-off and back-step geometry), and then finally on Coandă jet configured S809 airfoil in its operational configuration.

(a) (b)

Figure 11. Flow Fields of S809 Airfoil (a) with, and (b) without - Coandă -jet

To address three dimensional wind-turbine configurations, particularly for the optimum design of a Horizontal Axis Wind-Turbine (HAWT), logical and physical adaptation should be made, taking into account the fact that different airfoil profiles may be employed at various radial sections. Certain assumptions have to be made in order to project the two-dimensional simulation results to the three-dimensional case, which may be necessary to evaluate the equivalent Betz limit.

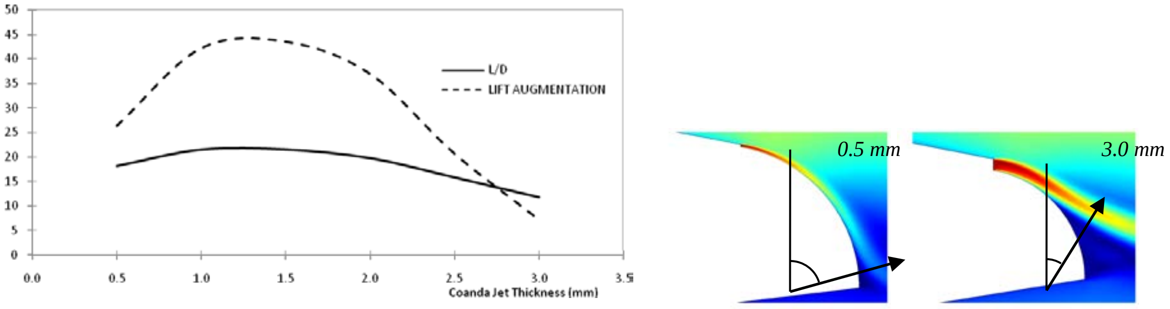
The flow fields in the vicinity of the trailing edge for both configurations are shown in Figures 11a and 11b. Careful inspection of these figures may lead to the identification of the geometry of the flow that could contribute to increased lift, in similar fashion as that contributed by flap, jet-flap or Gurney flap. Figure 11b typifies the flow field around Coandă configured S809 airfoil without Coandă jet (only with its back-step configuration), for further reference.



(a) (b) (c)

(d)

Figure 12. (a) The effect of TE radius on L/D with Coandă-jet (b) Lift coefficient (c) Drag coefficient; (Re =1 x10^6) (d) Velocity flow field for different TE radius; $C_\mu = 0.005$, t_{jet} = 1 mm)



(a) (b)

Figure 13. (a) The effect of jet thickness on the L/D and lift augmentation (b) Flow separation with different Coandă jet thickness (Re = 1 x 10^6, R = 10 mm $C_\mu = 0.005$,)

The trailing edge radius plays an important role in the Coandă configured design airfoil, since it may positively or negatively influence the downstream flow behavior. Thongcitpakdee [28-29] had claimed that the lower surface at the TE of the applied Coandă jet should be flat in order to minimize the drag when the jet is turned off.

Also, as reported earlier by Abramson and Rogers [52-53] in the late 1980’s, in spite of ability to generate more lift, the technique has not in general been applied to production aircrafts. Many of the roadblocks have been associated with the engine bleed requirements and cruise penalties associated with blown blunt trailing edges. In addition, there is a tradeoff between the use of a larger radius Coandă -configured airfoil for maximum lift and a smaller radius one for minimum cruise drag.

In contrast to the needs of trailing edge rounding-off radius, performance degradation associated with it always stands as an issue due to the drag penalty when the jet is in the off mode. To overcome such draw-back, the TE radius should be specificallly and carefully designed. For that purpose, simulations at several TE radius (from 10mm to 50mm) have been performed, at a fixed Coandă jet momentum coefficient C_μ ($C_\mu = 0.003$, considered just enough to fit with the wind turbine application), and at a constant free-stream velocity of $V_\infty = 14.6\ {}^{m}\!/_{sec}$ (Re= 1 x 10^6), to investigate the effect of TE radius on the aerodynamic characteristics of Coandă configured airfoils.

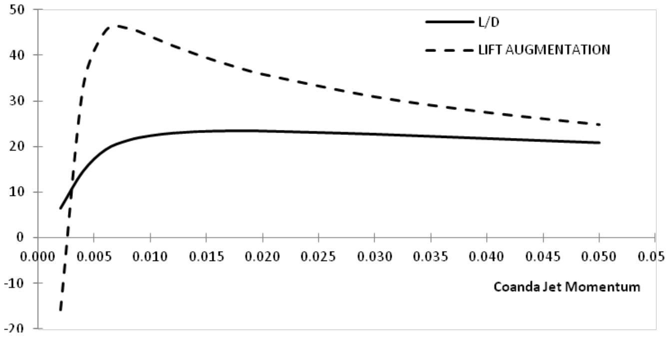
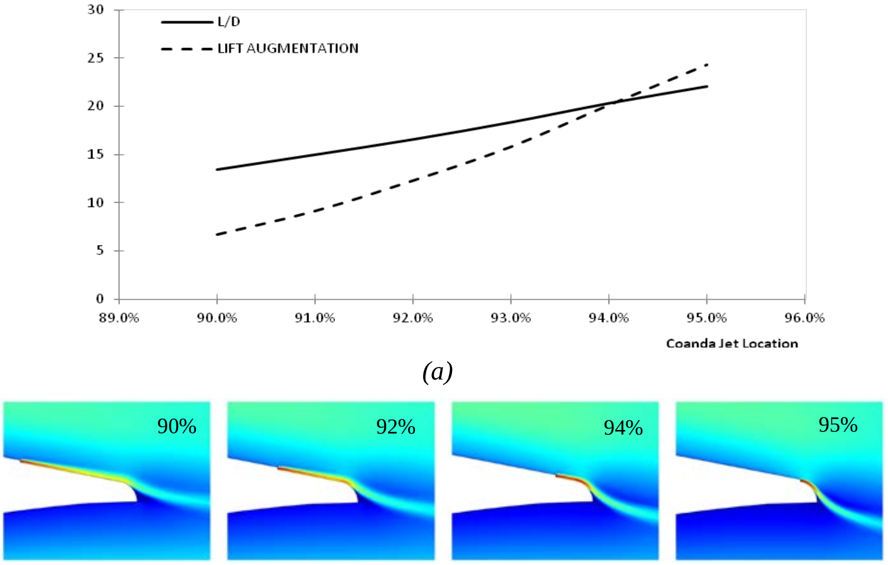


Figure 14. The effect of jet momentum on the L/D and lift augmentation (Re = 3.95 x 10^5, R_{TE} = 50 mm, t_{jet} = 1 mm)

Results exhibited in Figure 12 show that a higher ${}^{L}\!/_{D}$ can be achieved with a smaller TE radius (30 mm), and that the ${}^{L}\!/_{D}$ is decreasing as the TE radius is increased from 30 mm to 50 mm. The effect of TE radius on the lift augmention does not seem to be significant, as exhibited by the dashed line in Figure 8a. However, when the TE radius is increased beyond certain value (in Figure 8, >> 35 mm), the TE rounding-off seems to be ineffective, even detrimental.

Variation of the Coandă jet thickness from 0.5 mm to 3.0 mm at a fixed C_μ ($C_\mu = 0.005$), and at a constant free-stream velocity of $V_\infty = 14.6\ {}^{m}\!/_{sec}$ (Re= 1 x 10^6) is performed to investigate the effect of Coandă jet thickness (also called jet-slot-thickness) on the aerodynamic characteristics of Coandă configured airfoils. From Figure 13, it is found that a higher L/D can be achieved with a smaller Coandă jet thickness (1.0-1.5 mm), and that the L/D is decreased rapidly as the Coandă jet thickness is increased from 1.0 mm to 3.0 mm. A similar behavior is observed for the lift augmention as exhibited by the dashed line in Figure 13. However, generating a smaller jet requires higher pressure than a larger one at the same momentum coefficient. Since higher lift with as low mass flow rate as possible is preferred, a thin jet is more beneficial than a thick jet. From aerodynamic design perspective, within the range of agreeable power to generate Coandă -jet, a smaller Coandă jet thickness is preferred, although further careful trade-off study should be made. The performance of Coandă configured airfoils is dependent on the jet momentum conditions, which are important driving parameters. Figures 14 shows numerical simulation for a free-stream velocity of 5.77 m/sec.



(a)

(b)

Figure 15. (a) The effect of Coandă jet location on the L/D and lift augmentation (b) Velocity flow field for different Coandă jet location (Re = 1 x10^6, R_{TE} = 10 mm, t_{jet} = 1 mm, $C_\mu = 0.010$)

At very low jet momentum coefficient $C_\mu << 0.005$, the jet velocity is too low to generate a sufficiently strong Coandă effects that eliminates separation and vortex shedding. The lift to drag ratio L/D increases significantly with the increase of the jet momentum coefficient (C_μ) until the jet momentum coefficient reaches $C_\mu > 0.01$. After this value, the effect is otherwise. Under fixed free-stream velocity and fixed Coandă jet thickness, the total mass flow rate increases linearly with the increase of the jet momentum. Also the jet velocity ($V_{\text{Coandă jet}}$) has to be increased with the mass flow rate to keep a constant C_μ. The dotted line shown in Figure 14 shows that the maximum lift augmention is slightly above 60.

Contribution of Coandă Jet Momentum to Wind-Turbine Power

It should be noted that for the purposes of the present work, a uniform jet velocity profile has been adopted; this could be readily modified for more realistic modeling or design requirements. Numerical results indicate that there exists an optimum Coandă jet configuration, which has been the subject of parametric study as exhibited in Figures 8 – 11 for S809 airfoil. A significant design parameter for boundary condition, which has been utilized to characterize Coandă jet application by many investigators [10-15, 18-20], is specified by the momentum coefficient of the jet, C_μ.

For two-dimensional modeling, an equivalent jet momentum coefficient C_μ^* can be defined as:

$$C_\mu^* \equiv \frac{\dot{m} V_{Coandajet}}{\frac{1}{2}\rho V_\infty^2 A_{ref}} = \frac{\rho V_{Coandajet}^2 t_{Coandajet}}{\frac{1}{2}\rho V_\infty^2 c_{airfoil}} \tag{5}$$

This expression shows that for a given constant C_μ, changing the thickness of the Coandă jet will affect C_μ favorably.

To justify the results of the present study, and to give us a physical explanation of the effect of Coandă -jet, one may attempt to carry out simple calculation using first principle and Kutta-Joukowski law for potential flow, and compare the Lift of the Coandă jet configured airfoil with the clean one obtained using COMSOL™ 4.2. CFD code.

$$LLVVh_{CoandajetAirfoilcleanAirfoil} = \quad + \rho_{\infty} \left({}_{CoandajetCoandajet} - \right) \tag{7}$$

where $h_{Coandajet}$ is the moment arm of the Coandă jet with respect to the airfoil aerodynamic center. One then may arrive at a very good conclusion on the contribution of the Coandă jet to the lift (surprisingly, using COMSOL™ 4.2. CFD results for the lift ($L_{CoandajetAirfoil}$) values, the accuracy obtained by using equation (3) was in the order of 1.39%). However, care should be exercised to insure valid modeling for comparison.

For the three-dimensional configuration, there is a physical relationship between the Wind-Turbine shaft torque (which is a direct measure of the shaft power extracted) with C_μ, and in the actual three-dimensional case, the wind-turbine rotor yaw angle [28-29]. From the numerical results gained thus far, it can be surmised that circulation control, which in this particular case obtained by utilizing Trailing-edge Coandă -jet, can considerably increases the torque generated through the L/D increase gained.

The maximum theoretical power that can be extracted from the free stream (ambient air) is given by the Betz limit:

$$P_{Betz} = \frac{8}{27} \rho A_{Wind-turbine\ rotor} V_{\infty}^{2} \tag{6}$$

(where V_∞ is the free-stream wind speed). With the use of Coandă -jet, assuming the jet energy can be drawn from the inner part of the free-stream in the vicinity of the wind-turbine rotor hub, the Coandă jet additional power output corresponding to the jet momentum coefficient should contribute to the increase of shaft power output given by the theoretical Betz limit. Tongchitpakdee studies [28] also indicated such results. It should be noted that the ambient air free-stream wind speed V_∞ for the Wind-Turbine is different from the V_∞ implied in the present two-dimensional parametric study, which is the resultant of the ambient-air wind speed and the rotational speed of the particular section of the rotor blade.

Conclusions

CFD numerical experiments have been carried out to elaborate work reported earlier [25-27], with the objective to verify the favorable effects of Coandă -configured airfoil for enhanced aerodynamic performance and obtain some guidelines for the critical features of Coandă jet configured airfoil. Care has been exercised in the choice of turbulence model and other relevant parameters commensurate with the grid fineness desired, in particular since the number of grid utilized is relatively small in view of the desk-top computer utilized capabilities. Comparison of the numerical computation results for some baseline cases with experimental data under similar conditions lends support to the present computational parametric study.

The results show that the introduction of Coandă jet on S809 Coandă configured airfoil carried out in the present work confirms its effectiveness in enhancing L/D, which depends on the jet velocity. Rounding-off of the TE along with the introduction of the

Coandă jet seems to be effective in increasing L/D in airfoil specifically designed for Wind-Turbine, here exemplified by S809. Within the limits of local boundary layer thickness, there is a certain range of effective and optimum Coandă jet thickness commensurate with the airfoil dimension. With specific design specifications related to the Coandă jet thickness and TE rounding-off size, the Coandă jet momentum needed to improve the performance (lift augmentation due to jet) should not be excessive but sufficient to delay separation until the tip of the TE (where the upper surface meets the lower one). In addition, the Coandă jet should be placed sufficiently close to the TE to avoid premature separation.

Numerical results presented have been confined to zero angle-of-attack case, which has been considered to be very strategic in exhibiting the merit of Coandă jet as lift enhancer. The numerical studies could be extended to increasing angle of attack to obtain more comprehensive information, for which the choice of turbulence model will be more crucial.

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Nomenclature

CFD	Computational Fluid Dynamic
CCW	Circulation Control Wing
R	Trailing edge radius (mm)
C	Airfoil chord length (m)
L	Lift force (N)
D	Drag force (N)
H	Coandă jet thickness (mm)
L/D	Lift over drag ratio
R/C	Trailing edge radius over airfoil chord length ratio
H/C	Coandă jet thickness over airfoil chord length ratio
TE	Trailing Edge
STOL	Short Takeoff Landing
y^+	Dimensionless wall distance for a wall-bounded flow
u_τ	Friction velocity
y	Distance to the nearest wall
v	Kinematic viscosity
τ_w	Wall shear stress
ρ	Density
μ_τ	Turbulent Viscosity, as defined by Equation (2)
HAWT	Horizontal Axis Wind Turbine
M	Mach number
C_μ	Turbulent Model Constant, as defined by Equation (2)

C_μ	Momentum coefficient
$\frac{\Delta C_L}{C_L}$	Lift augmentation
MW	Megawatt
MWh	Megawatt hour

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