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The influence of surface temperature on Coanda effect

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Abstract

Coanda effect is the adhesion of fluid on a convex surface. This paper presents the effect of temperature on the Coanda flow and shows how the temperature of the surface can influence the flow behaviour. It has been found that there are two mechanisms which influence the flow behaviour; both have contrary effect on the flow. One is based on variable Prandtl number and another is based on constant Prandtl number (thermal diffusivity) effect. The increment of the thermal diffusivity has prolonged separation of the boundary layer, while other mechanism triggers the earlier detachment of the flow from the curved surface. The preliminary CFD evaluation has provided the important controlling parameter for the thrust deflection.

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Keywords: Coanda effect, surface temperature, adhesion, boundary layer, Prandtl number, momentum boundary layer, thermal diffusivity

1. Introduction

The ACHEON (Aerial Coanda High Efficiency Orienting-jet Nozzle) Project is a European 7th Framework Programme Level 0 project about the study of the application of a novel dual stream Coanda nozzle, which can realize a dynamic deflection of a synthetic high-speed jet. It has been financed to verify its applicability to aeronautic propulsion [1].

Any study on Coanda effect could not avoid considering some fundamental literature references, which constitutes the minimal preliminary basis for any further work. The reference study of any study on Coanda effect is the experimental activity by Newman [2] which has studied the boundary layer nature and effect. Davenport [3] has

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produced an effective analysis of the deflection of a thick jet by a convex surface. Favre-Marinet *et al* [4] has analyzed the instability of Coanda adhesion during a specific study on oscillating jets. Roberts [5] has produced an effective model of turbulence during Coanda Adhesion. Bradshaw [6] has investigated the effects of the streamline curvature on the Coanda adhesion of a Turbulent Flow. Strykowski, and Krothapalli [7] have investigated the possibility of active controls on Coanda effect nozzles. Kim [8] has studied general guidelines for the design of a Coanda ejector. Several systems have been adopted to control the adhesion of the fluid to the Coanda Surfaces [9-11]:

1. high speed superficial jets;
2. electromagnetic plasma discharge;
3. creation of small surface depressions.

The two initial methods ensures an effective control of adhesion by accelerating the fluid adjacent to the Coanda surface while the third method aims to enhance the adhesion encouraging the fluid jet reattachment or to enhance the adhesion.

Nomenclature

R	radius of curvature
k	turbulent kinetic energy
P	Reynolds averaged pressure
U	Reynolds averaged velocity
u'	fluctuating velocity
T	Reynolds averaged temperature of the surface
t	time
t'	fluctuating temperature
θ	angle of adhesion

2. ACHEON project and the progress of knowledge about coanda effect

The ACHEON project analyses an innovative nozzle (Figure 1), which is based on the unstable adhesion of two jets 1 and 2 to two Coanda surfaces. Referring to Figure 1 the following conditions can be identified:

1. if the momentum of the primitive jet (2) is greater than the one of (2’) the synthetic jet (4) adheres to the Coanda surface designated as (3);
2. if the momentum of the primitive jet (2’) is greater than the one of (2) the synthetic jet (4) adheres to the Coanda surface designated as (3’);
3. if momentums are equal the synthetic jet is straight aligned with the nozzle axis.

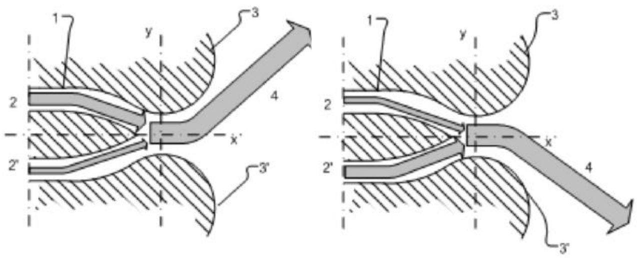

Figure 1 – Schematic diagram of the nozzle (from Trancossi [11])

The angle formed by the synthetic jet (4) and the geometrical axis of the nozzle can be controlled by the momentums of the primitive jets (2) and (2’). It can be increased when the difference between the moments of the two primitive jets (2) and (2') increases, can be decreased when it decreases and becomes null when it is zero.

Inside the ACHEON project, several studies about Coanda flow and its potentialities have performed focusing on several cases, which have not been previously in depth analyzed in the scientific literature, enriching the possibility of comprehension of Coanda effect and opening new direction for future. In particular, Trancossi [11] have performed a detailed literature survey focusing on the architecture and behaviour of different nozzle architectures. This work has been completed by Pascoa *et al* [12] analyzing in detail the effects of dielectric barrier discharge on the Coanda adhesion. Trancossi and Dumas [13] have started the analysis of the ACHEON nozzle considering it propelled by high quality ducted fan units for RC models. Trancossi *et al* [14] have defined a still preliminary but effective mathematical model of the Coanda adhesion in the nozzle by integral equations. Subhash and Dumas [15] have performed the boundary layer analysis for such kind of flow defining the strong influence of the shear stress. They demonstrate that it is necessary to consider wall shear stress, which has neglected by some studies in aeronautics, is evidently necessary in order to produce an adequate model of the adhesion of the flow to a curved surface.

3. Thermal effects on the adhesion

The natural and intrinsic instability of the ACHEON nozzle forces to analyze the effects of the disturbances which can influence the adhesion of a fluid stream to a surface. This paper introduces a forward step towards this study and aims to study the thermal behaviour on the flow over the Coanda surface. The importance of the study can be realized that the gas emanating from the propulsion system is encountered by the convection heat transfer from the surface to the gas can be able to influence vectoring of the thrust. However, this behaviour of the flow for this particular study has not been deeply analyzed yet, because most of the attention of aeronautic research has focused on low surface temperatures. Therefore, the basic physical laws, which govern the phenomenon, are not known in depth.

In this paper a numerical analysis is attempted to understand the effects of thermal exchanges control on the stability of Coanda adhesion. The present study aims to produce an effective increase of attention on a field of research, which could open interesting perspectives for the future, considering the obtained results.

4. Governing Equations

The mass and momentum conservation equations are given in the Reynolds Averaging form

$$\frac{\partial U_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = \frac{-1}{\rho}\frac{\partial P}{\partial x_i} + \nu \frac{\partial^2 U_i}{\partial x_j \partial x_j} - \frac{\partial}{\partial x_j}\overline{u_i' u_j'} \tag{2}$$

$$\frac{\partial T_i}{\partial t} + U_j \frac{\partial T_i}{\partial x_j} = \frac{-1}{\rho}\frac{\partial P U_i}{\partial x_i} + \alpha \frac{\partial^2 T_i}{\partial x_j \partial x_j} - \frac{\partial}{\partial x_j}\overline{t' u_j'} \tag{3}$$

4.1 SST k- ω Model [16]

The kinematic eddy viscosity is given by

$$\nu_T = \frac{a_1 \cdot k}{max\ \ a_1\omega, SF_2} \tag{4}$$

The following terms are also defined:

Turbulent kinetic energy:

$$\rho \frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = P_k - \beta^* k\omega + \left[\; \nu + \sigma_k \nu_T \; \frac{\partial k}{\partial x_j} \right] \tag{5}$$

Specific dissipation rate:

$$\frac{\partial \omega}{\partial t} + U_j \frac{\partial \omega}{\partial x_j} = \alpha S^2 - \beta\omega^2 + \frac{\partial}{\partial x_j}\left[\; \nu + \sigma_\omega \nu_T \; \frac{\partial \omega}{\partial x_j} \right]$$
$$+2 \;\; 1 - F_1 \;\; \sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_i} \frac{\partial \omega}{\partial x_i} \tag{6}$$

Closure coefficient and auxiliary equations are given by:

$$F_2 = \tanh\left[\left[\max\left(\frac{2\sqrt{k}}{\beta^* \omega y}, \frac{500\nu}{y^2 \omega}\right)\right]^2\right] \tag{7}$$

$$S^2 = \left| \frac{1}{2} \;\; \partial_j u_i + \partial_i u_j \;\; \right|^2 \tag{8}$$

$$F_1 = \tanh\left[\left[min\left(max\left(\frac{2\sqrt{k}}{\beta^* \omega y}, \frac{500\nu}{y^2 \omega}\right), \frac{4\sigma_{\omega 2} k}{CD_{k\omega} y^2}\right)\right]^4\right] \tag{9}$$

$$P_k = min \;\; G, 10\beta^* k\omega \tag{10}$$

$$G = \nu_T \frac{\partial U_i}{\partial x_j}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) \tag{11}$$

$$CD_{k\omega} = \max\left(2\rho\sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j}, 10^{-10}\right) \tag{12}$$

$$\phi = \phi_1 F_1 + \phi_2 \;\; 1 - F_1 \tag{13}$$

The model constants are given by as follows:

$$\alpha_1 = 5/9, \alpha_2 = 0.44, \beta_1 = 3/40, \beta_2 = 0.0828, \beta^* = 0.09$$

$$\sigma_{k1} = 0.85, \sigma_{k2} = 1, \sigma_{\omega 1} = 0.5, \sigma_{\omega 2} = 0.856$$

5. Grid Generation and solution Methodology

The grid has been produced in the Gambit (2012) [17] and the boundary layer resolved appropriately as shown in figure 2 and 3. The radius of curvature is 0.025 m and diameter of the jet is 0.01 m. Computation has been performed with commercial software Fluent 6.3 (2012) [17]. The grid independent check has been performed according to the ERCOFTAC [18] guidelines and as described in the following papers [19, 20].

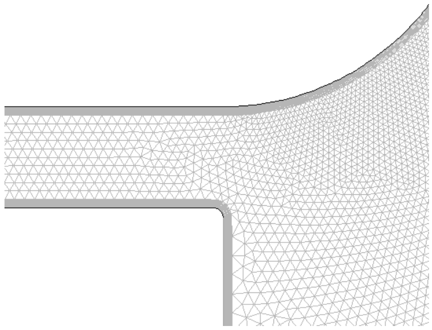

Figure 2 - Grid generation (detain near the nozzle)

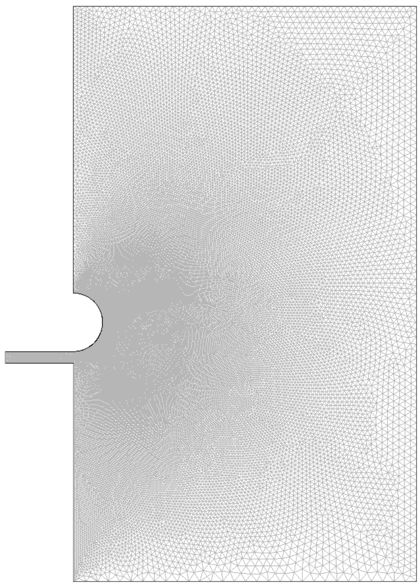

Figure 3 - Grid generation (visualization of the full domain)

The optimum number of grid (numerically stable grid) has been determined through the numerical computation of the grid at different refinement level of the grid at the curved surface. It has been found that, when the grid resolved the viscous sub-layer until y+ value less than two, then one can get the jet deflection angle independent of the grid. We have used SST K-ω [16] model.

Second order upwind scheme has been used to discretize of momentum equation and of k and ω model. The pressure and velocity has been coupled through the PISO (Pressure-Implicit with Splitting of Operators) method

[21]. Pressure gradient term has been discretized using the PRESTO (PREssure STaggering Option) method [22]. The PRESTO scheme provides improved pressure interpolation in situations where large body forces or strong pressure variation are present.

Unsteady term has been discretized using first order implicit method taking advantage of unconditionally stable with respect to time step size, which has been as taken $\Delta t = 1\times10^{-03}$ s.

6. Results and Discussion

The computations have been performed for the velocity 20, 50, 80 m/s for the given geometry. The temperature of the curved surface has been specified at 100 °C and 600 °C. The velocity contours for the selected case has been given in figure (4(a)-(d)). The velocity contours shows that the induced velocity at the curved surface due to the pressure gradient. The small vortex formation at the outer core of jet is evident by the irregular shape of velocity contours. Thermal effect on the flow has been analyzed as shown in table 1. Increment of the temperature of curved surface induced the earlier detachment of the jet.

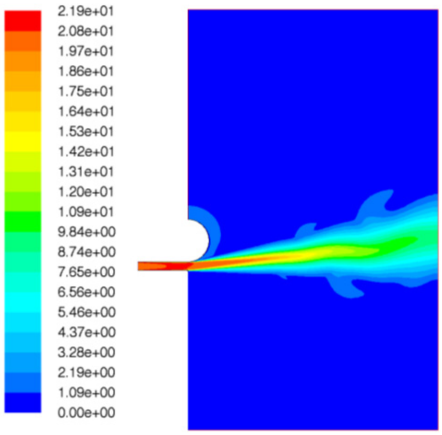

Figure 4(a) - V = 20 m/s, temp= 100 °C and θ= 6.515°

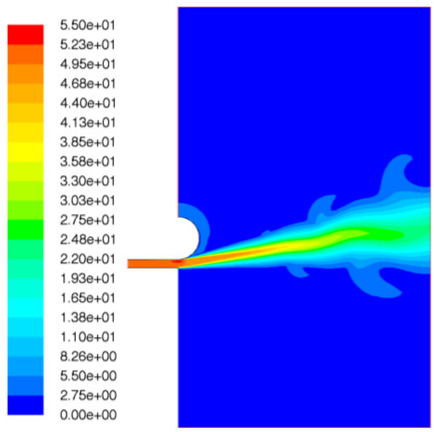

Figure 4(b) - V = 50 m/s, temp= 100 °C and θ= 10.168°

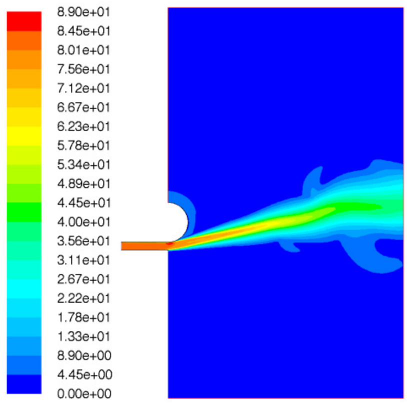

Figure 4(c) - V = 80 m/s, temp = 100 °C and θ= 14.098°

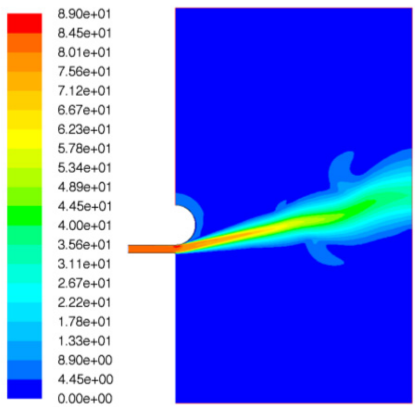

Figure 4(d) - V=80 m/s, temp = 600 °C and θ = 12.437°

A possible interpretation has been formulated. When the fluid flows over the heated curved surface in proximity of the curved surface as the temperature of the curved surface increases, dynamic viscosity of the fluid at the vicinity of the wall is increasing with respect to the fluid which is far from the curved surface. Then the thermal heat capacity of the fluid near to surface is increasing, and then consequently, the Prandtl number of the fluid near the curved surface is increasing. In this way the momentum boundary layer would be increasing resulted in the decreased adhesion angle.

The second mechanism can also be given by assuming the constant Prandtl number. Increasing the jet velocity, the thermal gradient near the surface is increasing and the thermal boundary layer would be decreased and consequently the momentum boundary layer would be decreased. In this way the adhesion angle would be increased. Consequently, the observed earlier detachment happens by the effect of the complex equilibrium of the above-mentioned effects.

Table 1: Variation the adhesion angle with respect to temperature

Temp(°C)	Velocity (m/s)	Θ(°)
100	20	6.515
600	20	5.623
100	80	14.098
600	80	12.437
100	50	10.168
600	50	9.034

However, the high temperature of the curved surface certainly enhances the thermal diffusivity of the flow and increases the momentum of the jet.

On one side, this mechanism will enhance the initial adhesion to the curved surface and can inhibit the earlier detachment of the jet. On the other, it accelerates the late detachment of the jet.

In this computational study, the first mechanism (variable Prandtl number) effect seems to be more dominant over the second mechanism (constant Prandtl number). One can find the demarcation line, where the thermal diffusivity would be dominant over the other mechanism. The present study indicates that for higher velocity (than present study), the second mechanism (constant Prandtl number) could be pronounced effect on the flow. Than with increasing, the temperature of the curved surface there would be larger adhesion angle of the flow. The temperature profile for the all velocity has plotted in figure 8. It shows that the cooling effect of the Coanda surface increases with velocity.

The results appear in line with the theory of convection [23], which affirms that the convection increases when velocity increases. The temperature profile remains the same at all velocities. It allows thinking that a relation of proportionality directly relates the heat transfer to the jet velocity.

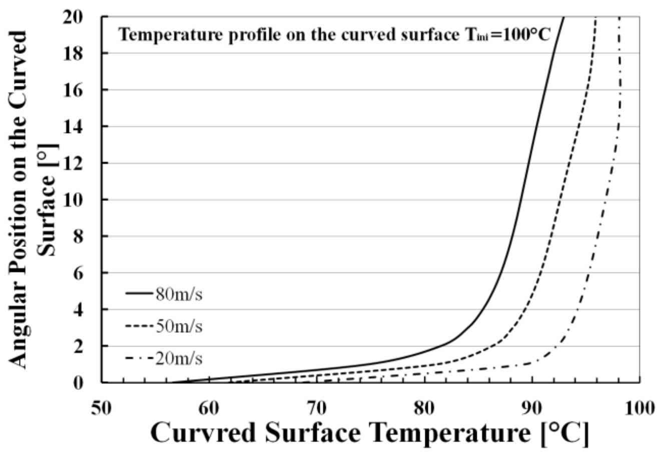

Figure 5- Temperature profile on the curved surface

7. Conclusion

In the present paper, the behaviour on the flow over a Coanda surface at different temperature has been analyzed. It has produced some interesting elements, which need to be validated through experiment. The variable Prandtl number mechanism appears more pronounced than the constant Prandtl number. Therefore, an earlier detachment of the boundary layer has observed. The temperature profile for jet velocity pointed out the variable Prandtl number. It can be noticed also that, for higher velocities, the thermal diffusivity (const. Prandtl number) can play a dominant role over the heat transfer behaviour. This study aims to open a possible door for the development of a future research in order to investigate the mechanism in detail. In particular, it is necessary to perform theoretical, numerical and experimental analysis, to understand better the complex relations between thermal diffusivity and internal forces during Coanda effect adhesion. In particular, it is necessary to understand better the crucial role of the thermal diffusivity during the stream adhesion over a Coanda surface. It is also interesting to investigate in depth the how heat transfer influences the boundary layer and the detachment phenomena,

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