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# Scaling investigation of plasma-induced flows over curved and flat surfaces: comparison to the wall jet

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## Abstract

The present investigation deals with Dielectric Barrier Discharge (DBD) induced jets flowing over curved surfaces and studied in the framework of a circulation control application, carried out by acting near the rounded trailing-edge of an airfoil. These jets are characterised experimentally via Particle Image Velocimetry (PIV) in quiescent air conditions. The study assesses the evolution of these flows in terms of self-similarity of the mean flow and of its turbulent components. DBD wall jets evolution in the streaming direction is also analysed through the rate of spread and the maximum velocity decay evolution as commonly done for fluidic wall jets, and also through several normalised quantities deriving from different length and velocity scales. A comparison with a canonical flow, such as the classical wall jet flowing over plane or curved surfaces, is made in order to find out the similarities and the discrepancies between these two flows. Results reveal that DBD wall jets and canonical fluidic wall jets show comparable properties in the diffusion zone. Compared to the plane DBD wall jet, centrifugal forces are responsible of the greater spread of curved DBD wall jets and are likely the source of instabilities leading to their transitional state. The momentum flux of the induced jet and the radius of curvature of the surface are two relevant scales for DBD induced flows developing over curved surfaces.

*Keywords:* DBD, curvature effect, plasma wall jet

## 1. Introduction

In the field of active flow control, plasma-based actuators are widely used to achieve flow manipulation and enhance aerodynamic performances over a large range of applications (e.g., aerospace, wind energy, aeronautics, turbomachinery). However, these kinds of actuators are not yet mature for industrial applications as reported in Kriegseis et al. (2016). Nevertheless, surface plasma actuators based on a Dielectric Barrier Discharge (DBD) are frequently studied because of their easy implementation, short time-response and versatility. In the domain of flow control over airfoils, many studies have analysed the aerodynamic effects of this actuation which can be used to successfully achieve boundary layer separation control (Post and Corke (2004)), circulation control by acting near a rounded trailing-edge (Zhang et al. (2011), Meijerink and Hoeijmakers (2011), Kotsonis et al. (2014) and Baleriola et al. (2016)) or by the implementation of Gurney flaps with plasma induced jets (Feng et al. (2015)), and boundary layer transition control (Schuele et al. (2013), Lovig et al. (2014) and Yadala et al. (2018)) among others.

As in all flow control studies, the analysis in quiescent air conditions of the flow induced by DBD actuators needs

to be carried out to characterise the induced jet development over the model surface and to investigate the mechanisms of interaction with the external flow. Furthermore, this kind of characterisation is helpful for the implementation and validation of phenomenological models (Shyy et al. (2002), Suzen et al. (2005)), PIV-based computational methods (Maden et al. (2013)) or physics-based approaches (Boeuf et al. (2007), Rogier et al. (2014)) that seek to numerically reproduce the DBD induced flows involved in flow control applications. Indeed, it is relevant to determine if classical laws used to model DBD induced jets and based on plane wall jet analogies are still valid for less conventional surfaces such as curved ones. This characterisation also provides the induced jet velocity profile evolution as a function of the applied voltage, which is necessary to estimate the momentum coefficient, commonly used to assess the strength and efficiency of the actuation as done in Sosa et al. (2007) and Kotsonis et al. (2014), for example.

Previous studies in quiescent air are conducted with actuators implemented on a flat configuration. However, as far as DBD circulation control over an airfoil with a rounded trailing-edge is concerned, it is necessary to study the development of the induced flow evolving along a curved wall. It is within this framework that the present study was carried out. To investigate experimentally, at a wind-tunnel scale, the airfoil lift increase or decrease, DBD plasma actuators were implemented over an airfoil

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52 model designed with a specific rounded trailing-edge (TE)<sub>109</sub>  
 53 as reported in [Baleriola et al. \(2016\)](#). Due to the dimen-<sub>110</sub>  
 54 sions of the model designed for wind-tunnel tests, the cur-<sub>111</sub>  
 55 vature radius of the rounded trailing-edge is of an order<sub>112</sub>  
 56 of magnitude equal to a few millimeters. More conven-<sub>113</sub>  
 57 tional circulation control strategies are traditionally im-<sub>114</sub>  
 58 plemented by means of concepts including shape change,<sub>115</sub>  
 59 TE flaps or air blowing and often rely on the Coanda effect<sub>116</sub>  
 60 that keeps a tangential jet attached over a curved surface.<sub>117</sub>  
 61 Whereas blowing techniques usually show high momentum,<sub>118</sub>  
 62 coefficients ([Joslin and Jones \(2006\)](#)), it is not possible to<sub>119</sub>  
 63 achieve similar performances so far with DBD actuators<sub>120</sub>  
 64 due to their inherent limitation to produce a high level<sub>121</sub>  
 65 of momentum, in spite of the promising outcomes of the<sub>122</sub>  
 66 numerical approach proposed by [Zhang et al. \(2010\)](#). AC-<sub>123</sub>  
 67 cording to [Joslin and Jones \(2006\)](#) and demonstrated by  
 68 [Kotsonis et al. \(2014\)](#) and [Baleriola et al. \(2016\)](#), lift in-<sub>124</sub>  
 69 crease achieved thanks to circulation control is mainly due  
 70 to a mechanism of boundary layer separation manipula-<sub>125</sub>  
 71 tion around the trailing-edge which modifies the mixing of<sub>126</sub>  
 72 the near wake without totally suppressing it. Neverthe-<sub>127</sub>  
 73 less, by considering specific arrangements of electrodes, it<sub>128</sub>  
 74 is possible to produce a tangential jet over a curved wall<sub>129</sub>  
 75 with a small radius of curvature that will stay more or less<sub>130</sub>  
 76 attached to the surface. Several DBD actuators were used<sub>131</sub>  
 77 for the intended flow control application. Their induced<sub>132</sub>  
 78 flows were characterised in quiescent air conditions and<sub>133</sub>  
 79 constitute the working basis of this study. <sub>134</sub>

80 Generally, DBD induced jets are compared to fluidic<sub>135</sub>  
 81 wall jets even if some differences remain between them.<sub>136</sub>  
 82 In the case of a DBD induced jet, the electrically charged<sub>137</sub>  
 83 particles close to the wall are accelerated from the active<sub>138</sub>  
 84 electrode and along the grounded one, following the elec-<sub>139</sub>  
 85 trical field. This particle motion entrains the ambient air<sub>140</sub>  
 86 in the same direction along the wall, creating an induced<sub>141</sub>  
 87 jet. There is no nozzle or jet exit and the flow accelerates<sub>142</sub>  
 88 continuously until roughly the end of the last grounded<sub>143</sub>  
 89 electrode. The velocity magnitude induced by a single<sub>144</sub>  
 90 DBD is weak (max.  $\approx 8$  m/s as in [Moreau \(2007\)](#)) com-<sub>145</sub>  
 91 pared to most fluidic jets. In the case of a DBD induced<sub>146</sub>  
 92 jet, there is no mass addition by the actuator but only<sub>147</sub>  
 93 mass entrainment and momentum transfer. <sub>148</sub>

94 The present study focuses on the experimental char-<sub>149</sub>  
 95 acterisation by PIV (Particle Image Velocimetry) of the<sub>150</sub>  
 96 plasma induced jets evolving along a specific airfoil with<sub>151</sub>  
 97 a rounded trailing-edge as a function of the electrode ar-<sub>152</sub>  
 98 rangement and without an external flow. In order to high-<sub>153</sub>  
 99 light the effects of possible centrifugal forces on curved<sub>154</sub>  
 100 induced jets, a DBD induced jet in a flat configuration<sub>155</sub>  
 101 equivalent to the curved ones was also studied. Induced<sub>156</sub>  
 102 jets main features were analysed by using dimensional and<sub>157</sub>  
 103 normalised variables commonly used for fluidic wall jets.<sub>158</sub>  
 104 This approach made it possible to assess the transition<sub>159</sub>  
 105 of such plasma induced jets from a laminar to a turbu-<sub>160</sub>  
 106 lent regime and to evaluate the evolution of DBD induced<sub>161</sub>  
 107 flows in terms of self-similarity of the mean flow and of its<sub>162</sub>  
 108 turbulent components as well as in terms of rate of spread<sub>163</sub>

and maximum velocity decay evolution. Furthermore, this  
 analysis enabled us to determine whether or not plasma in-  
 duced jets show similar properties as canonical fluidic wall  
 jets but also to determine which are the most relevant vari-  
 ables to describe the evolution of the jets along a curved  
 wall. The causes leading to the jet transition to turbulence  
 were also investigated.

First, a short review of previous investigations on fluidic  
 wall jets and on DBD induced jets is presented to intro-  
 duce the comparison between these two flows. Then, the  
 mean topology of curved DBD flows is analysed for three  
 actuator positions around the airfoil trailing-edge. The  
 third part establishes the basis for the fourth section that  
 studies the streamwise evolution of the induced jets in the  
 jet-related coordinate system.

### 1.1. Fluidic wall jets

[Förthmann \(1936\)](#) studied the wall jet (WJ) for the first  
 time and theoretically compared it to the free open jet.  
 Assuming  $x$  as the WJ streaming direction, the author  
 proved that the jet maximum velocity decreases as  $x^{-\frac{1}{2}}$   
 and that the jet spread, defined as the maximum velocity  
 half-width, linearly evolves along the  $x$ -direction. In addi-  
 tion, velocity profiles from different distances to the nozzle  
 proved to be coincident in one curve showing a similarity  
 law.

A wall jet can be divided into two distinct layers on both  
 sides of the velocity peak as introduced by [Glauert \(1956\)](#).  
 On the one hand, the inner layer is located between the  
 wall and the maximum velocity ordinate. Due to the in-  
 fluence of the wall, [Glauert \(1956\)](#) predicted that this zone  
 would behave as a turbulent boundary layer, whereas the  
 outer layer would be similar to the shear layer of a free  
 jet. As the WJ develops, the inner layer becomes wider  
 and the maximum velocity decreases. However, jet veloc-  
 ity decreases faster than spread increases. This implies  
 that the local Reynolds number of the jet, based on the  
 maximum jet velocity and its related velocity half-width,  
 slowly decreases with the jet development.

The wall jet development can also be described in the  
 streamwise direction and be characterised by three dis-  
 tinct zones: the potential core, where the nozzle exhaust  
 velocity is preserved; a transitional region where the flow  
 shifts progressively from a laminar to a turbulent regime,  
 and a fully developed zone where the flow is completely  
 turbulent. One of the main difficulties is to determine  
 the critical jet Reynolds number  $Re_{jc}$  corresponding to  
 the transitional regime. [Kurtz and Crandall \(1962\)](#) stud-  
 ied theoretically the natural convection on a heated ver-  
 tical plate on air and found a  $Re_{jc}$  of 161. [Chun and  
 Schwarz \(1967\)](#) carried out a theoretical study on the sta-  
 bility of an incompressible, viscous plane WJ subjected to  
 small disturbances and  $Re_{jc}$  was determined to be about  
 57. An experimental stability investigation of a lami-  
 nar two-dimensional plane WJ was carried out by [Ba-  
 jura and Szweczyk \(1970\)](#). The authors concluded that

164 the critical value of  $Re_{jc}$  lies between 500 and 2000. Ba-220  
 165 jura and Catalano (1971) studied a transitional plane WJ221  
 166 (Reynolds number between 100 and 600) and found that222  
 167 Kelvin-Helmholtz instability of the free shear layer plays223  
 168 an important role in the WJ transition. Schneider and224  
 169 Goldstein (1994) carried out a detailed analysis on the225  
 170 turbulent WJ evolution with three different measurement226  
 171 techniques (pressure probe, Laser Doppler Anemometry227  
 172 and Hot Wire Anemometry).228

173 Bradshaw and Gee (1960) carried out experiments on a229  
 174 WJ developing over a circular cylinder. The growth of the  
 175 curved WJ thickness proved to be linear and equal to 1.5  
 176 times that of the plane WJ. According to the authors, this230  
 177 thickness increase may be caused by a negative radial gra-231  
 178 dient of angular momentum that causes a centrifugal insta-232  
 179 bility on the turbulent flow. The authors defined an angle  
 180  $\theta^*$  from the nozzle to the azimuthal position of the veloc-233  
 181 ity profile. In their experiment, the curved WJ remained234  
 182 attached to the wall until an angle  $\theta^*$  of  $150^\circ$ . An in-depth235  
 183 study on the plane WJ was carried out by Wygnanski et al.236  
 184 (1992) and pursued by Neuendorf and Wygnanski (1999)237  
 185 who also examined the WJ development around a circu-238  
 186 lar cylinder. The rate of spread and the velocity decay of239  
 187 the curved WJ appeared to be greater than those of the240  
 188 plane WJ, as were the levels of turbulence and Reynolds241  
 189 stresses.

### 1.2. Wall jets induced by DBD actuators

191 Wall jets induced by DBD actuators (DBD-WJs) have  
 192 been studied only on plane configurations. Table 1 shows  
 193 a summary of DBD-WJ characteristics found in the litera-  
 194 ture. Only publications showing velocity profile investiga-  
 195 tions relevant to this study are cited. The table specifies  
 196 the type of actuator, the method used for the measure-  
 197 ment of the velocity profiles, the maximum jet velocity  $U_j$ 242  
 198 and its corresponding thickness (maximum velocity half-243  
 199 width)  $b$  and jet Reynolds number  $Re_j$ . A precise defini-244  
 200 tion of these variables is given below in section 3.1. For245  
 201 thick dielectrics (thicker than 2 mm) the jet velocities are246  
 202 between 3 and 5 m/s and jet thicknesses between 2 mm and247  
 203 5 mm at the end of the last grounded electrode (beginning248  
 204 of jet diffusion). This leads to Reynolds numbers from 400249  
 205 to 900 suggesting that the plane DBD induced jets found250  
 206 in the literature are laminar or in a transitional regime.251  
 207 DBD-WJs seem to be similar to laminar WJs as pointed252  
 208 out by Roth et al. (2004) and Jukes et al. (2006). As for253  
 209 fluidic WJs, jet velocity decay seems to evolve as  $x^{-\frac{1}{2}}$  and254  
 210 jet thickness as  $x^{\frac{3}{4}}$  (or  $x$ ). Murphy et al. (2013) found that255  
 211 as the voltage is increased, and hence the Reynolds num-256  
 212 ber, the velocity peak of the velocity profile shifts closer257  
 213 to the wall. The authors also calculated the evolution of258  
 214 the standard deviation of the longitudinal velocity  $\sigma_u$  for a259  
 215 large range of Reynolds numbers and found a  $\sigma_u$  increase260  
 216 with  $Re_j$  up to a Reynolds number of 100. Beyond this261  
 217 value a  $\sigma_u$  plateau was reached. The authors suggested262  
 218 that the WJ generated by a DBD actuator becomes tur-263  
 219 bulent at  $Re_{jc} \approx 100$ . In Maden et al. (2013) the authors264

used PIV measurements and numerical computations to  
 study DBD-WJs. Their  $Re_j$  was about 370 and the ve-  
 locity peak location moved towards the wall as the jet  
 developed. Boucinha et al. (2008a), Murphy et al. (2013)  
 and Maden et al. (2013) found the maximum velocity or-  
 dinates between laminar and turbulent WJ profiles. DBD  
 induced flows have low Reynolds numbers and appear to  
 be laminar although some instabilities exist and natural  
 transition may occur downstream of the actuator, as with  
 other dynamic flow control devices.

## 2. Mean topology of the flow induced by a DBD actuator along a curved surface

### 2.1. Experimental set-up

The airfoil used for the flow control application was a  
 NACA65<sub>4</sub>-421 airfoil with a rounded trailing-edge as em-  
 ployed in Baleriola et al. (2016) for circulation control.  
 The model has a chord  $c$  equal to 0.3 m and is 1.1 m wide.  
 The radius of curvature  $R$  of the TE is 2% of the chord  
 (6 mm). The model (figure 1) is composed of a front main  
 part, from the leading-edge to 70% of the chord, and of  
 a removable trailing-edge. The trailing-edge is itself com-  
 posed of a holder and a cap both made of PMMA.

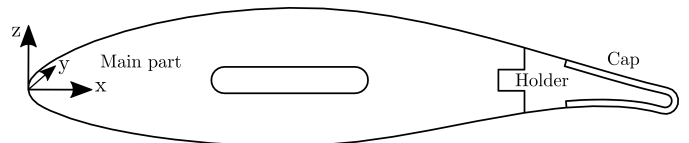


Figure 1: Side view of the model

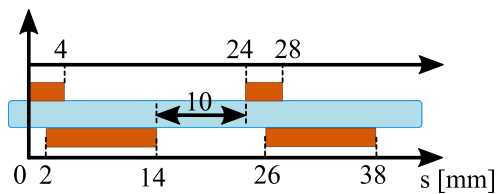
#### 2.1.1. DBD plasma actuators

Figure 2 shows the top view and the geometry of the  
 electrodes of the actuators used. The grounded elec-  
 trodes are linear (strip electrodes) and 12 mm wide. The  
 high voltage electrodes are serrated (triangular pattern  
 in series) in order to ensure plasma homogeneity along  
 the wingspan and to avoid uneven discharge distributions  
 (Matsuno et al. (2016)) in the intended flow control ap-  
 plication. All the actuators used are made up of two sin-  
 gle DBD actuators in a row. All the electrodes used are  
 copper electrodes (85  $\mu\text{m}$  thick) and are separated by the  
 3 mm-thick PMMA dielectric of the model cap. The use  
 of a thick dielectric allows the generation of a thicker in-  
 duced wall jet with higher jet velocities compared to thin  
 dielectrics. The grounded electrodes are encapsulated by  
 the dielectric of the model itself (holder part). To pre-  
 vent plasma formation in the opposite flow direction, ac-  
 tive electrodes are partly covered with a layer of polyimide  
 film. The spanwise length of the actuators is 900 mm.

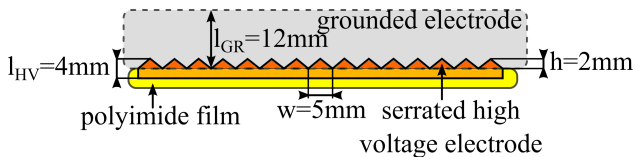
Three positions of the multi-DBD actuator were stud-  
 ied and are shown in figure 3. The electrode arrangement  
 and the distances between the electrodes are identical for  
 the three positions, the only difference is their position

Publication	Actuator type	Method	$U_j$ [m/s]	$b$ [mm]	$Re_j$
Roth et al. (2004)	SDBD (ceramic, 0.635 mm)	PP	3.2	2	410
Pons et al. (2005)	SDBD (glass, 4 mm)	PP	3.25	2.5	520
Jukes et al. (2006)	Symmetric DBD (Mylar, 250 $\mu$ m)	HWA	0.51	1.3	45
Forte et al. (2007)	SDBD (glass, 2 mm)	PP	4	2	510
Boucinha et al. (2008a)	SDBD (Mylar and Kapton, 0.7 mm)	LDV	3.8	1	240
Moreau et al. (2008)	Sliding DBD (PMMA, 4 mm)	PP	4.2	3	800
Balcon et al. (2009)	SDBD (PMMA, 3 mm)	PIV	2.7	5	860
Benard et al. (2009)	S2DBD (PMMA, 3 mm)	PP	3.8	1.7	410
Debien et al. (2011)	ExDBD (PMMA, 3 mm)	PIV	4.2	3	800
Durscher and Roy (2012)	SDBD (acrylic, 3 mm)	PIV & PP	4	2	510
Erfani et al. (2012)	SDBD (Kapton, 0.3 mm)	PIV	1.2	2	150
Maden et al. (2013)	SDBD	PIV & num.	-	-	370
Murphy et al. (2013)	SDBD (Kapton, 0.36 to 0.45 mm)	PIV	-	-	20-250
Benard and Moreau (2014)	SDBD (PMMA, 3 mm)	PP	5	2.8	900
Belan and Messanelli (2015)	Serrated SDBD (PMMA, 2 mm)	PP	3.2	1.5	300

Table 1: Overview table of plane DBD-WJ characteristics from previous studies (SDBD: Single DBD, S2DBD: Single two-electrode DBD, ExDBD: Extended DBD)



(a) Geometry of a plane multi-DBD actuator



(b) Top view of the electrodes

Figure 2: Geometry and top-view of the electrodes

around the trailing-edge of the airfoil. The actuator im-297  
 plemented in *position A* starts blowing well before the TE<sub>298</sub>  
 curvature and its second active electrode is located before<sub>299</sub>  
 the curvature. The electrodes corresponding to *position B*<sub>300</sub>  
 are centered on the middle line of the TE, the second ac-<sub>301</sub>  
 tive electrode being just before its center line. *Position C*<sub>302</sub>  
 has its set of electrodes shifted by an angle of 45° towards<sub>303</sub>  
 the lower side of the airfoil with respect to the TE center<sub>304</sub>  
 line. An equivalent plane configuration was also tested for<sub>305</sub>  
 comparison with the curved induced jets. <sub>306</sub>

These actuators are intended to perform circulation con-<sub>307</sub>  
 trol: two actuators were designed to increase the lift force<sub>308</sub>  
 (*Pos. B* and *Pos. C*) and one to decrease it (analogous<sub>309</sub>  
 to *Pos. C* but blowing in the opposite direction, from the<sub>310</sub>  
 lower side to the upper side of the airfoil). The effective-<sub>311</sub>  
 ness of the actuation was proved through load and pressure<sub>312</sub>  
 measurements and a lift coefficient increase of about  $\pm 0.1$ <sub>313</sub>

282 was performed in the linear part of the lift curve. The  
 283 whole pressure distribution around the airfoil was modi-  
 284 fied despite the fact that the action takes place solely at  
 285 the trailing-edge. The input electrical parameters (voltage  
 286 and frequency) employed in this study correspond to this  
 287 flow control application.

### 2.1.2. Electrical set-up

288 The power supply employed is a laboratory-made supply  
 289 composed of a Crown amplifier (XS1200 series, 22 Hz -  
 290 22 kHz, 2.3 kW) and of a single-phase transformer made by  
 291 Trabo (90 V - 20 kV, 2 kW, 20 Hz - 20 kHz). The maximum  
 292 voltage output is about 20 kV and 2 kW. The sinusoidal  
 293 function generator is a TTi (TGA1241, 40 MHz, 10 V).  
 294 The applied high voltage is measured with a high voltage  
 295 Tektronix probe (P6015A series, 75 MHz, 3 pF).  
 296

### 2.1.3. PIV set-up

The actuators were characterised in quiescent air condi-  
 tions using a PIV system. Trailing-edges were tested in-  
 side an enclosed box (1.1 m  $\times$  0.5 m  $\times$  0.5 m) with a seeding  
 arrival and an aspiration system that can remove seed-  
 ing particles if required. The laser is a Nd:Yag Quan-  
 tel Twins (Ultra series, 2  $\times$  200 mJ, 532 nm) coupled with  
 a laser sheet generator lens. Images were recorded with  
 a TSI PowerView 4M Plus camera with a sensor size of  
 2048 px  $\times$  2048 px and equipped with a Nikon 200 mm fo-  
 cal length objective set at an f-number of 5.6. Image  
 pairs were recorded at a frequency of 4 Hz and were anal-  
 ysed with the Insight 4G software of TSI. In the case of  
 the curved configurations, the final interrogation window  
 was 32 px  $\times$  32 px and an overlap factor of 50% was used.  
 The dimensions of the field of view were 60 mm  $\times$  60 mm  
 and the vector fields were produced at a final resolution

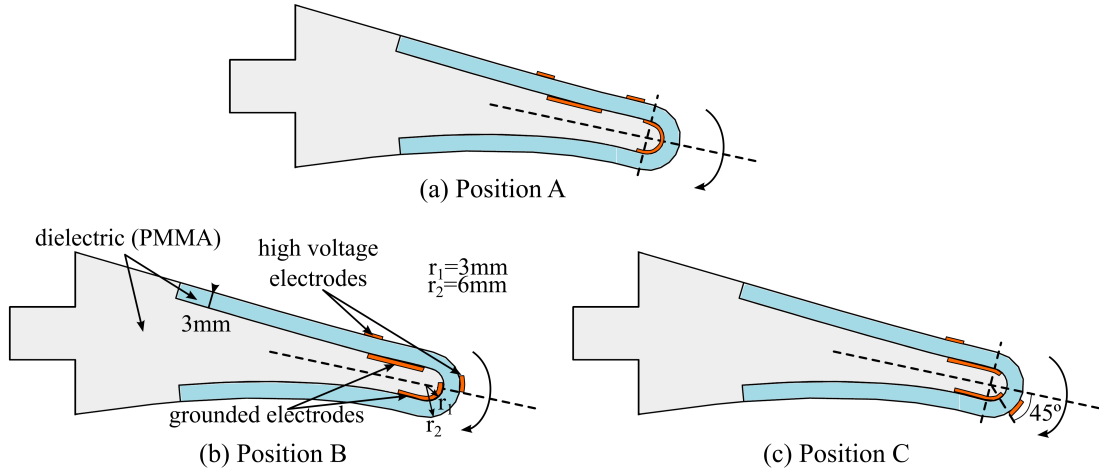


Figure 3: Drawing of electrode position around the trailing-edge of the airfoil

314 of 0.47 mm/vec (0.03 mm/px). Time averaging was per-351  
 315 formed with 600 image pairs. PIV analysis of the plane352  
 316 configuration was performed with different set-up param-353  
 317 eters due to the ensuing different geometry. The dimen-354  
 318 sions of the field of view were 102 mm  $\times$  102 mm and the355  
 319 final interrogation window was 16 px  $\times$  16 px with an over-356  
 320 lap factor of 50%. The final resolution was 0.4 mm/vec357  
 321 (0.05 mm/px). Time averaging was performed with 1000358  
 322 image pairs. In both cases, seeding particles were micro-359  
 323 sized olive oil droplets sprayed by a PIVTEC seeding sys-360  
 324 tem with a particle diameter of 1  $\mu$ m. The flow induced  
 325 by the plasma actuator is assumed to be two-dimensional  
 326 and PIV measurements were carried out in the plane of  
 327 symmetry of the airfoil TE or of the plane induced jet. In361  
 328 both plane and curved configurations statistical conver-362  
 329 gence for the mean flow and of its turbulent components363  
 330 was reached. 364

331 As mentioned in Prasad (2000), PIV errors can be de-365  
 332 composed in: (1) random errors, (2) bias errors, (3) gra-366  
 333 dient errors, (4) tracking errors and (5) acceleration er-367  
 334 rors. With the exception of random and bias errors, these368  
 335 errors are not deterministic and it is therefore difficult369  
 336 to give a quantitative estimation of the overall system-369  
 337 atic errors on the measured velocity fields. However, ex-370  
 338 periments were carried out carefully in order to minimise371  
 339 these errors. Wall reflections were reduced with the use of372  
 340 non-reflective coatings and the ensemble average of mini-373  
 341 mum intensity was subtracted from the raw images during374  
 342 the pre-processing as mentioned in Kotsonis (2015). Also,375  
 343 particle diameter was equal to about 2 px as suggested in376  
 344 Prasad (2000). The frame time interval was chosen such377  
 345 as particles are displaced of  $\frac{1}{4}$  of the final interrogation378  
 346 window as mentioned in Keane and Adrian (1990). Fur-379  
 347 thermore, during the post-processing, two passes were used380  
 348 with decreasing interrogation areas and a 50% overlap as381  
 349 also advised in Prasad (2000). Vectors were accepted if the382  
 350 ratio between the 1st and the 2nd correlation peaks was383

above 1.2 and a median filter was applied to the resulting  
 velocity field.

To quantify random errors, statistical uncertainty of the  
 mean velocity can be computed using the central limit  
 theorem (Coleman and Steele (2009)). This method was  
 recently used by Van Hooff et al. (2012) and Kaffel et al.  
 (2015) for the evaluation of the repeatability error of PIV  
 measurements on a plane WJ in a confined space and a  
 plane WJ subjected to an external lateral flow respectively.  
 The statistical error  $\widetilde{u}_r$  is defined as:

$$\widetilde{u}_r = \frac{1}{\sqrt{N_s}} z_{\frac{\alpha}{2}} \frac{U_{RMS}}{U} \quad (1)$$

where  $N_s$  is the number of samples,  $z_{\frac{\alpha}{2}}$  is equal to 1.96 for  
 a confidence interval of 95%,  $U_{RMS}$  is the local root mean  
 square velocity and  $U$  the mean velocity at the same loca-  
 tion. The uncertainty calculated in the worst configuration  
 (maximum  $U_{RMS}$ ) was about 2% for the plane configura-  
 tion and 3.5% for the curved ones.

## 2.2. Mean topology in the airfoil-related coordinate system

The airfoil-related coordinate system, named  $(x, y, z)$ , is defined as:  $x$ -axis in the direction of the airfoil chord,  $y$ -axis in the wingspan direction and  $z$ -axis in the vertical direction (see figure 4a). Velocity average and fluctuating parts are defined according to the following Reynolds decomposition where  $t$  represents the time dependency: longitudinal velocity defined as  $U(x, z, t) = \bar{U}(x, z) + u'(x, z, t)$  and vertical velocity as  $V(x, z, t) = \bar{V}(x, z) + v'(x, z, t)$ .

Figure 4 shows time-averaged velocity magnitude fields for the three configurations tested. Electrode position and geometry are superimposed in the figures. Normal velocity profiles are also plotted and are computed with a linear interpolation in the normal direction to the wall using a spatial step equal to the PIV resolution (0.47 mm/vec). Even though the three actuators are powered at the same

384 voltage  $V_{AC}$  and frequency  $f_{AC}$  (and therefore consume  
 385 the same electrical power), the three curved DBD-WJs  
 386 topologies are significantly different.

387 The induced WJ corresponding to *Pos. A* starts well  
 388 before the trailing-edge curvature, develops along the up-  
 389 per side of the airfoil and starts deflecting over the second  
 390 grounded electrode. This curved DBD-WJ does not fol-  
 391 low the TE curvature and detaches perpendicularly to the  
 392 airfoil chord, along the  $z$ -direction. The induced flow of  
 393 *Pos. B* partially follows the TE curvature but does not  
 394 remain perfectly attached to the model. On the contrary,  
 395 the DBD-WJ in *Pos. C* follows the wall curvature and  
 396 perfectly adheres to the model wall beyond the  $180^\circ$  sharp  
 397 turn. This different jet behaviour can be explained by the  
 398 electrode arrangement of the three actuators. For *Pos. A*,  
 399 the actuator ends too early to allow the TE circumvention.  
 400 In the cases of *Pos. B* and *Pos. C*, the region of EHD in-  
 401 teraction reaches the end of the TE curvature and the WJ  
 402 is forced to completely follow the sharp turn curvature.  
 403 However, the zone of EHD interaction of *Pos. C* reaches  
 404 the lower side of the airfoil and the induced jet can remain  
 405 perfectly attached to the model wall.

406 Electrode position has a direct impact on the DBD-WJ  
 407 topology, in particular on whether the induced jet is go-  
 408 ing to follow the model curvature or not. The reason why  
 409 DBD-WJs stay attached to the wall seems to be more an  
 410 electrical effect than a phenomenon due to the dynamics  
 411 of the fluid. Fekete (1963) studied the Coanda effect of  
 412 a WJ over a cylinder and pointed out that a complete  
 413 circumvention (separation at an azimuthal angle from the  
 414 nozzle of  $180^\circ$ ) occurs with high Reynolds numbers (over  
 415 20 000) and small ratios  $\frac{b}{R}$ ,  $b$  being the jet half-width and  
 416  $R$  the radius of curvature of the cylinder. The angle of  
 417 separation  $\theta_{sep}$  rapidly increases with the Reynolds num-  
 418 ber and tends to stabilize at  $Re_j = 30\,000$  at about  $210^\circ$ .  
 419 For low Reynolds numbers and ratios  $\frac{b}{R}$  under 0.05, the  
 420 author found  $\theta_{sep}$  equal to  $60^\circ$ ,  $75^\circ$ ,  $100^\circ$  and  $140^\circ$  for  
 421  $Re_j$  equal to 1500, 2000, 2500 and 5000 respectively. In  
 422 the present configuration, a curved DBD-WJ has a ratio  $\frac{b}{R}$   
 423 before reaching the TE equal to 0.66 which is quite a high  
 424 value. Vít and Maršík (2004) studied a heated Coanda  
 425 laminar WJ and for  $Re_j$  of 740 and 950 obtained an an-  
 426 gle  $\theta_{sep}$  of  $40^\circ$  and  $90^\circ$  respectively for a ratio  $\frac{b}{R} = 0.25$ .  
 427 Their results showed that over this ratio separation occurs  
 428 at even smaller  $\theta$  angles. Hence, the Coanda effect does  
 429 not seem to be applicable for the curved DBD-WJs of the  
 430 present study in view of the Reynolds numbers and jet  
 431 thicknesses involved.

### 432 3. Two-dimensional wall jet developing along 433 plane or curved surfaces

434 This section establishes the nomenclature used in the  
 435 following analysis and introduces the necessary variables.

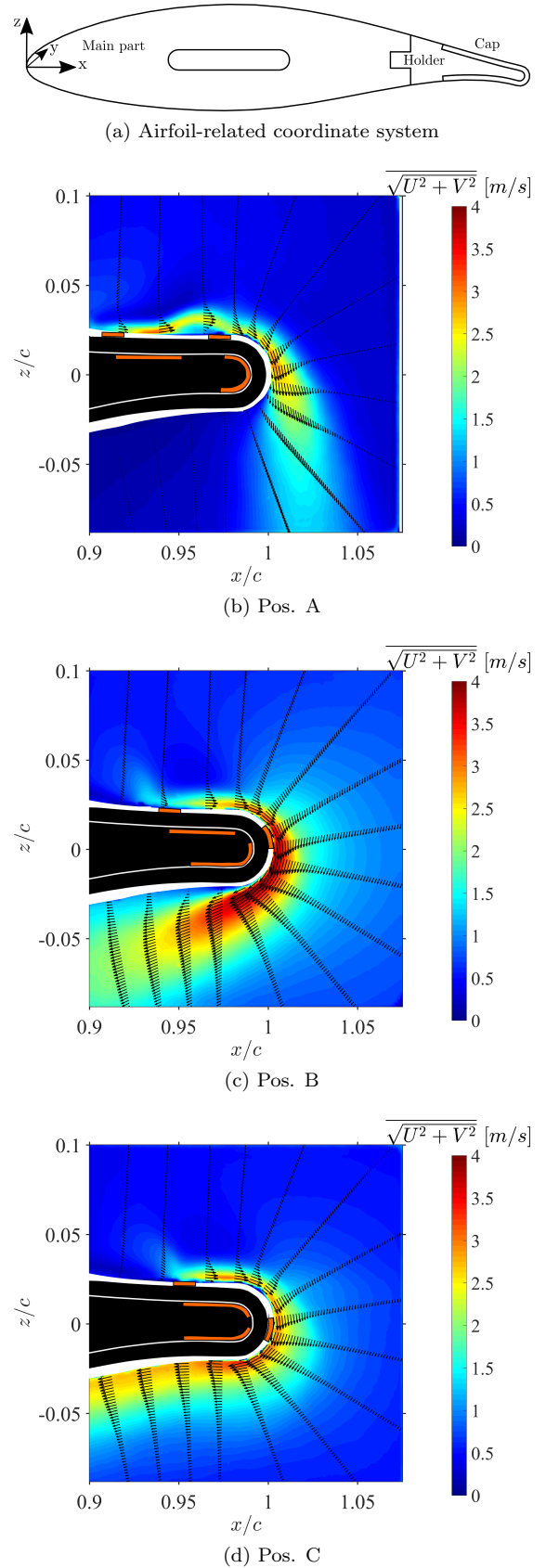


Figure 4: Time-averaged velocity fields for the three electrode positions in quiescent air conditions ( $V_{AC} = 18\text{ kV}$  and  $f_{AC} = 1\text{ kHz}$ )

### 3.1. Plane and curved wall jet variables

To analyse the wall jet development over a plane surface some quantities are usually defined as shown in figure 5. A new coordinate system related to the WJ and different from the one presented in the section above is defined here. It is defined in such a way that the abscissa  $x$  is in the longitudinal direction of the flow and the ordinate  $z$  in the normal direction. The origin of the  $x$ -coordinate is the exit of the nozzle and the  $z$ -coordinate origin is the surface of the wall. Each velocity profile along the  $x$ -coordinate has its local maximum velocity named  $U_{max}(x)$  located at a distance  $z_{max}(x)$  from the wall. The variable  $z_{1/2}(x)$  is defined as the distance from the wall to the location at which the mean velocity decreases to one half of its local maximum value in the outer flow. The jet maximum velocity  $U_j$  is the jet velocity slightly downstream of the exit of the nozzle, at the  $x_0$  abscissa defined as  $U_{max}(x_0) = U_j$ . The Reynolds number of the jet is defined as  $Re_j = \frac{U_j b}{\nu}$  where  $b$  is the nozzle width and  $\nu$  is the kinematic viscosity of the flow. In the case of a plane DBD-WJ (see figure 6), as there is no physical nozzle, the origin of the  $x$  coordinate ( $x = 0$ ) is set at the beginning of the first active electrode and the abscissa of the virtual origin  $x_0$ , corresponding to the maximum jet velocity, is also defined as  $U_{max}(x_0) = U_j$ . The virtual slot width  $b$  is defined as the jet thickness at the virtual origin  $b = z_{1/2}(x_0)$ . Assuming that the surface discharge has a negligible effect on the gas properties as mentioned in Moreau (2007), the kinematic viscosity of the induced jet is assumed to be equal to the kinematic viscosity of air. Then, the jet Reynolds number  $Re_j$  can be defined by analogy with the fluidic WJ defined above.

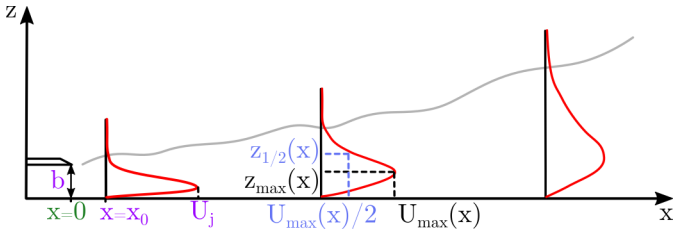


Figure 5: Scheme of a fluidic plane WJ over a plane surface and its specific variables

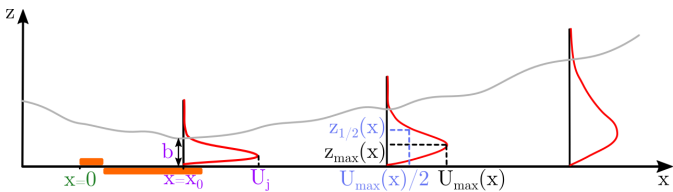
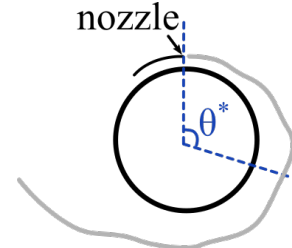


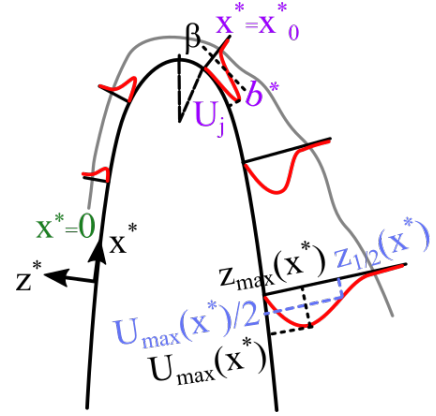
Figure 6: Scheme of a DBD-WJ over a plane surface and its specific variables

A second coordinate system is defined to follow a wall jet evolution over a curved surface. Neuendorf and Wygnanski (1999) studied a WJ flowing around a circular cylinder

and defined an angle  $\theta^*$  (figure 7a) between the nozzle and the azimuthal position of the velocity profile. In the present case (figure 7b), as the trailing-edge is not axisymmetric, a curvilinear abscissa  $x^*$  is defined along the curvature with a related vertical coordinate  $z^*$  normal to the model wall. The origin of the  $x^*$  coordinate ( $x^* = 0$ ) is set at the beginning of the actuator (first active electrode). Variables  $z_{max}^*(x^*)$ ,  $U_{max}(x^*)$  and  $z_{1/2}(x^*)$  are defined in the same way as for the plane WJ described above. Local variables such as the maximum jet velocity  $U_j$ , the virtual origin  $x_0^*$ , the virtual slot width  $b^*$  and the jet Reynolds number  $Re_j$  are also defined in accordance with the plane case. The angle  $\beta$  is defined as the angle between the trailing-edge extremity and the virtual origin  $x_0^*$ .



(a) Angle  $\theta^*$  definition



(b) Scheme of a DBD-WJ over a curved surface

Figure 7: (a)  $\theta^*$  angle definition over a cylinder, (b) Scheme of a DBD-WJ over a rounded trailing-edge and its specific variables

### 3.2. Scalings

Three different scalings will be considered in the following and are summarized in table 2. The first scaling (scaling 1) is the conventional normalisation that considers the virtual slot width  $b$  (or  $b^*$ ) as the length scale and the jet velocity  $U_j$  as the velocity scale. In Wygnanski et al. (1992) the authors demonstrated that self-similarity of a plane WJ depends on the momentum flux  $J$  as well as on the viscosity and density of the fluid leading to the second scaling (scaling 2):  $\frac{\nu^2}{J}$  is the length scale and  $\frac{J}{\nu}$  the velocity scale. The authors in Neuendorf and Wygnanski (1999) suggested a new normalisation for curved



	Scaling 1 (plane & curved WJ)	Scaling 2 (plane & curved WJ)	Scaling 3 (curved WJ)
Length scale	$b$	$\frac{\nu^2}{J}$	$\frac{R}{\sqrt{\frac{J}{R}}}$
Velocity scale	$U_j$	$\frac{J}{\nu}$	$\sqrt{\frac{J}{R}}$
Jet $Re$	$Re_j = \frac{bU_j}{\nu}$	—	$Re_N = \frac{\sqrt{JR}}{\nu} = \sqrt{\frac{\frac{1}{2}U_j^2 b^* R}{\nu^2}}$
Local $Re$	$Re_x = \frac{U_{max}(x)z_{\frac{1}{2}}(x)}{\nu}$	—	$Re_N(x^*) = \frac{\sqrt{J(x^*)R}}{\nu}$

Table 2: Summary of the three employed scalings

WJs (scaling 3) involving the radius of curvature  $R$  as the length scale and  $\sqrt{\frac{J}{R}}$  as the velocity scale. For both scalings 2 and 3 the kinematic momentum flux  $J(x)$  (or  $J(x^*)$ ) is defined as:

$$\begin{aligned}
J(x) &= \int_{z=0}^{\infty} U^2(x, z) dz \\
&= z_{\frac{1}{2}}(x) U_{max}^2(x) \underbrace{\int_{\frac{z}{z_{\frac{1}{2}}}=0}^{\infty} \left( \frac{U(x, z)}{U_{max}(x)} \right)^2 d \left( \frac{z}{z_{\frac{1}{2}}} \right)}_{K(x) \approx \text{constant}} \\
&= z_{\frac{1}{2}}(x) U_{max}^2(x) K(x)
\end{aligned} \quad (2)$$

which gives at the nozzle or virtual origin  $x_0$  (or  $x_0^*$ ):

$$\begin{aligned}
J_0 &= J(x_0) \\
&= z_{\frac{1}{2}}(x_0) U_{max}^2(x_0) \underbrace{\int_{\frac{z}{z_{\frac{1}{2}}}=0}^{\infty} \left( \frac{U(x_0, z)}{U_{max}(x_0)} \right)^2 d \left( \frac{z}{z_{\frac{1}{2}}} \right)}_{K(x_0) = K_0} \\
&= b U_j^2 K_0
\end{aligned} \quad (3)$$

It should be noted that  $J_0$  is a constant for a given induced jet whereas  $J(x)$  is a local variable that evolves with the WJ development. For scaling 3, the authors redefined the Reynolds number as  $Re_N = \frac{\sqrt{JR}}{\nu}$ .

#### 4. Characterisation of DBD wall jets in the jet-related coordinate system

##### 4.1. Jet main characteristics

Table 3 shows the DBD induced jet characteristics for the actuators studied. The Reynolds numbers of the jets are shown according to the two definitions specified in table 2.

In the case of *Pos. A* powered at 18 kV, the virtual origin  $x_0^*$  is located at an angle  $\beta$  with respect to the TE extremity equal to  $-10^\circ$  whereas for *Pos. B* and *Pos. C* it is located at  $60^\circ$  and  $70^\circ$  respectively. The position of the virtual origin is directly related to the WJ topology and

therefore to the position of the electrodes around the TE: the more the DBD-WJ attaches to the model curvature, the greater the  $\beta$  angle. While the jet velocity magnitude  $U_j$  is equivalent between plane and curved DBD-WJs, the jet thickness  $b$  (or  $b^*$ ) remains smaller for the plane cases leading to lower Reynolds numbers. The Reynolds number  $Re_j$  for curved DBD-WJs varies from 1100 to 1900 whereas the one according to Neuendorf's definition  $Re_N$  ranges from 900 to 1200 and is more uniform for all the actuators and voltages tested. This is due to the magnitude of the length scales  $b$  and  $\sqrt{bR}$  used in the Reynolds numbers  $Re_j$  and  $Re_N$ . In our case  $b \approx 7$  mm and  $\sqrt{bR} \approx 6.6$  mm which leads to a  $Re_N$  slightly smaller than  $Re_j$ . This is not the case in Neuendorf and Wygnanski (1999) where  $Re_N$  is almost five times higher than  $Re_j$  because  $b \approx 2.3$  mm and  $\sqrt{bR} \approx 15$  mm. Whatever the Reynolds number definition used, all the DBD induced jets are in a transitional regime or not very far from it according to the critical Reynolds number suggested by Murphy et al. (2013) which is  $Re_{jc} \approx 100$  for DBD induced jets.

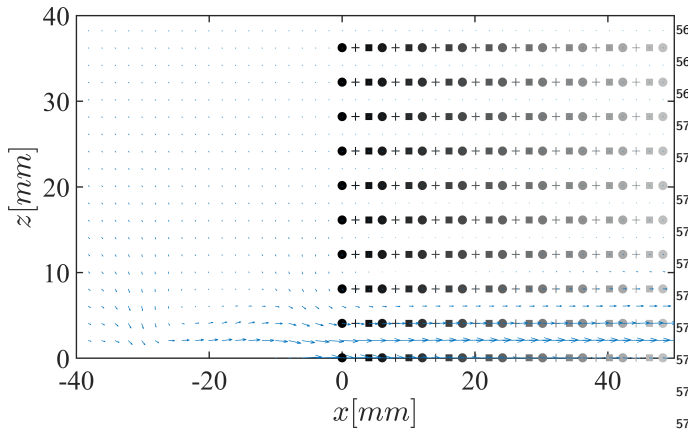
##### 4.2. Self-similarity of the mean velocity profiles and of the turbulent components

The objective of this section is to characterise the curved and plane induced jets in terms of velocity profiles and self-similarity. Both plane and curved DBD-WJs are powered at  $V_{AC} = 18$  kV but have distinct Reynolds numbers: 600 for the plane DBD and 1300 for the curved DBD in *Pos. C*. The latter curved case behaves the closest to the plane WJ of all the curved actuators studied, especially in the diffusion zone. Velocity profiles normal to the wall are computed in the jet-related coordinates  $(x^*, z^*)$ . The equation of the lines perpendicular to the surface and their angle with the horizontal direction are found. Then, the coordinates of the velocity profiles are computed in the curvilinear framework. Finally, the velocity values are linearly interpolated along the profile coordinates.

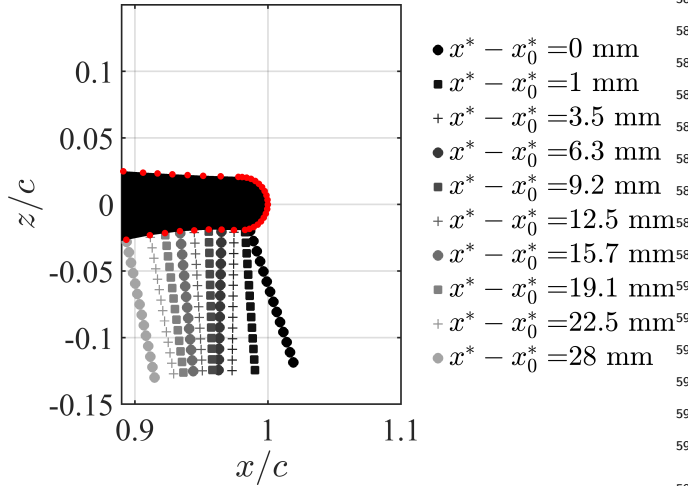
The analysed velocity profiles located in the diffusion zone of each actuator are shown in figures 8a and 8b for the plane and curved DBD-WJ respectively. Markers and line colors shown in the figures correspond to the ones employed all along the section at each given abscissa: the lighter the gray-scale color and the farther the profiles are in the jet streamwise direction.

	$V_{AC}$ [kV]	$b$ or $b^*$ [mm]	$U_j$ [m s <sup>-1</sup> ]	$\beta$ [°]	$Re_j$	$Re_N$
Pos. A	18	4.8	2.8	-10	860	680
Pos. B	15	7.2	3.4	50	1600	1000
	18	7.7	3.8	60	1900	1200
Pos. C	15	5.7	3.0	70	1100	800
	18	6.2	3.3	70	1300	900
Plane DBD	15	2.5	2.8	-	450	-
	18	2.9	2.9	-	600	-

Table 3: DBD-WJ characteristics



(a) Plane DBD



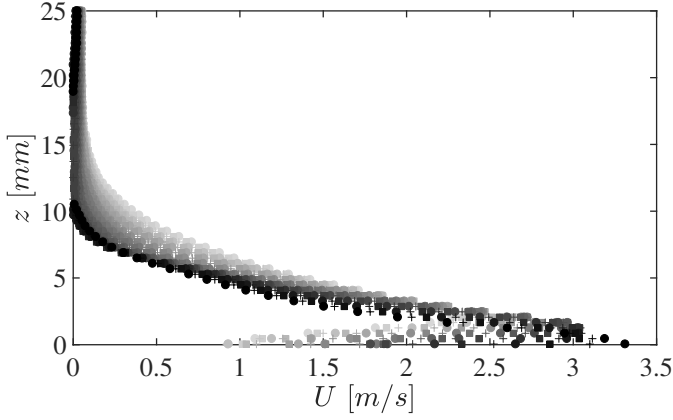
(b) Curved DBD

Figure 8: Location of the analysed velocity profiles and their respective markers

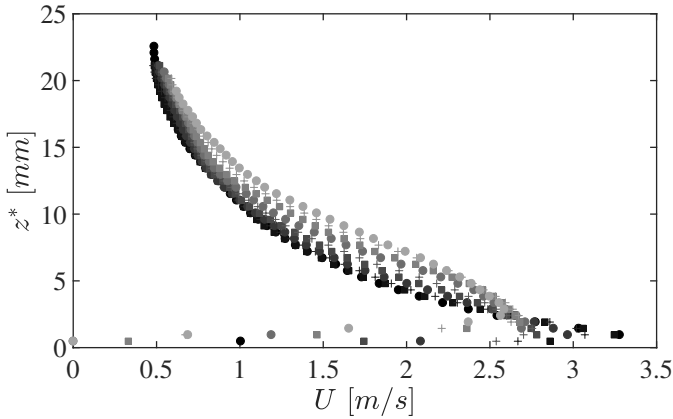
In the case of the curved DBD case, the first three profiles in the streamwise direction (darker colors) are right after the virtual origin  $x_0^*$ . Their velocity values are near the maximum value  $U_j$  and the profiles show a high velocity gradient in the vicinity of the wall.

As suggested in Bradshaw and Gee (1960) the greater spread of the curved WJ can be induced by two factors: entrainment, necessary for jet attachment to the wall but also a source of jet destabilisation, and centrifugal forces acting on the flow. DBD induced jets have the same order of magnitude of maximum velocity but a strongly different topology (see figure 10a). Indeed, curved jets show a higher  $z_{max}$  and are much thicker, especially in the outer jet zone (*Pos. B* thicker than *Pos. C*). A centrifugal force density  $f_{cent} = \rho\omega^2 r$  can be computed where  $\omega = \frac{U}{r}$  is the angular velocity of the flow and  $r$  the radial position with respect to the center of the trailing-edge curvature. Figure 10b shows the  $f_{cent}$  profiles for the two curved actuators at the virtual origin  $x_0^*$ . The profiles clearly show that the centrifugal force is higher for the DBD-WJ in *Pos. B* along all the jet outer zone, highlighting the greater spread and the incipient separation from the wall. It seems that the centrifugal force acts mainly on the outer part of the WJ rather than on the inner part. As mentioned in Neuen-dorf and Wygnanski (1999), it can be assumed that, along with centrifugal forces, entrainment induces large eddies that provoke a rapid spreading of the DBD-WJ with a non-negligible vertical velocity component and a turbulence enhancement that leads to the WJ separation.

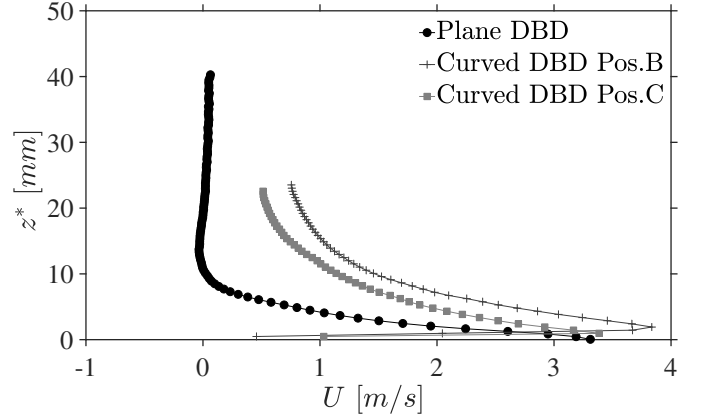
Figure 11a shows the flow rate  $Q = \rho \int_{z=0}^{\infty} U(x, z) dz$  per unit length for the two actuators studied in this section and figure 11b the evolution of the local momentum flux  $J$ . In both curves the use of a multi DBD actuation is evidenced as  $Q$  and  $J$  increase in two distinct steps along the acceleration zone. In the case of the curved DBD-WJ, beyond the virtual origin, there is a flow rate and a momentum plateau highlighting an equilibrium between external mass entrainment and jet diffusion. In the case of the plane DBD-WJ, after the virtual origin there is a slight but steady flow rate increase and a momentum decrease. Hence, in the plane configuration, mass entrainment along the jet direction feeds the induced WJ, increasing its flow



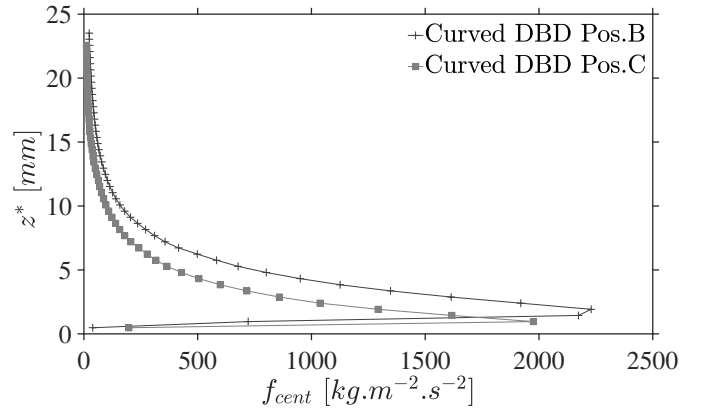
(a) Plane DBD (diffusion zone)



(b) Curved DBD (Pos. C - diffusion zone)



(a) Velocity  $U$



(b) Centrifugal force  $f_{cent}$

Figure 9: Dimensional velocity profiles at different  $x^*$  positions

Figure 10: Velocity  $U$  and centrifugal force  $f_{cent}$  profiles at the virtual origin  $x_0$  (or  $x_0^*$ ) for different actuators

609 rate and generating a momentum flux decrease.

610 The commonly used normalisation for velocity profiles is 632  
 611 scaling 1 and the corresponding velocity profiles are plotted 633  
 612 in figure 12. The plots also superimpose the laminar and 634  
 613 turbulent cases obtained by Glauert and Schneider respectively. 635  
 614 Regarding the plane DBD-WJ (figure 12a), this 636  
 615 scaling collapses the experimental data reasonably well except 637  
 616 the area in the very vicinity of the wall and the outer 638  
 617 flow where the data scatter becomes larger. The ordinate 639  
 618 of the maximum velocity is located at  $\frac{z_{max}^*}{z_1^*} = 0.35$  right 640

619 between the laminar and the turbulent profiles (0.6 for a 641  
 620 laminar WJ, 0.15 to 0.2 for a turbulent WJ). (Boucinha 642  
 621 et al., 2008b), Murphy et al. (2013) and Maden et al. 643  
 622 (2013) studied the evolution of plane DBD induced jets 644  
 623 and also found velocity profiles in between laminar and 645  
 624 turbulent ones. The velocity gradient in the inner part 646  
 625 seems closer to the laminar WJ, but the outer part tends 647  
 626 to follow the turbulent velocity distribution. In the case of 648  
 627 the curved DBD configuration (figure 12b), the profiles of 649  
 628 the higher abscissas  $x^*$  (lighter colors) fit well the turbu- 650  
 629 lent profile obtained by Schneider and Goldstein (1994) 651  
 630 but the first velocity profiles beyond the virtual origin 652  
 631 (darker colors) do not really fit either laminar or turbu- 653

609 lent profiles, probably due to the EHD force existing for  
 610 these profiles. However, the ordinate of  $\frac{z_{max}^*}{z_1^*}$  is equal to  
 611 0.15 in agreement with the turbulent velocity profile. This  
 612 first scaling does not perfectly collapse the mean velocity  
 613 distribution in one single curve but a quasi-similarity is  
 614 nonetheless reached. The ordinate of the maximum velocity  
 615 peak confirms that DBD-WJs are in a transitional  
 616 regime. The curved WJ matches the turbulent velocity  
 617 profile for the higher abscissas  $x^*$  almost perfectly.

A second normalisation usually used in shear flows involving  $z_1^*$ ,  $z_{max}^*$  and  $U_{max}$  is plotted in figure 13. This scaling has the characteristic of taking into account the increase in jet thickness. The normalisation does not collapse the data fully but is acceptable for the positive ordinates of the outer flow that tends to be similar to a free jet. In the inner region of the plane DBD induced jet, similarity is however not perfectly reached, particularly for the ordinates closer to the wall.

Figures 14 and 15 show velocity fluctuations and Reynolds stresses for plane and curved DBD-WJs respectively according to scaling 1. In the case of the plane DBD-WJ, self-similarity is clearly not obtained for the turbulent

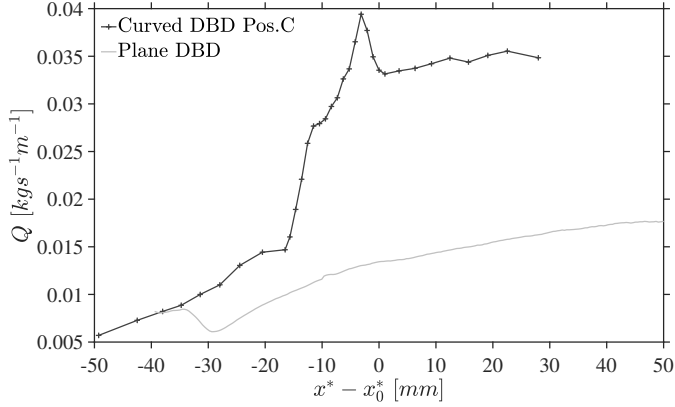
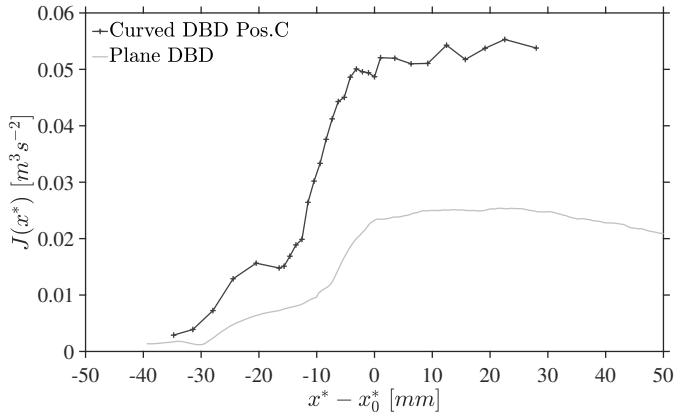
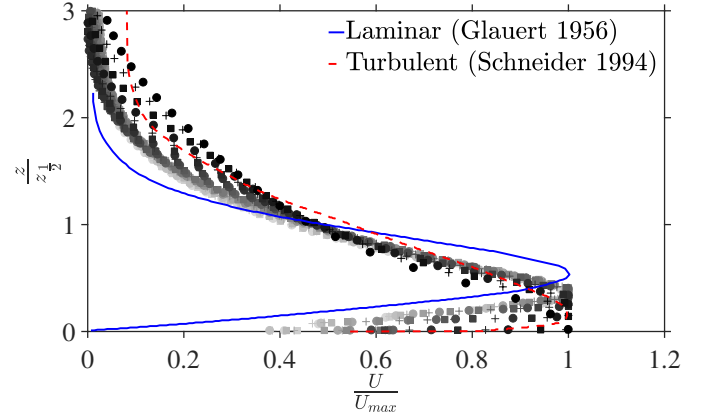
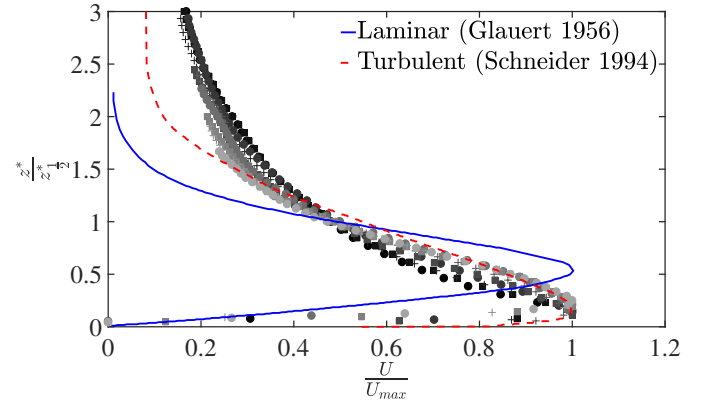
(a) Flow rate  $Q$ (b) Local momentum flux  $J$ 

Figure 11: Flow rate and momentum flux evolution in the jet direction



(a) Plane DBD (diffusion zone)



(b) Curved DBD (Pos. C - diffusion zone)

Figure 12: Normalised velocity profiles at different  $x^*$  positions based on scaling 1

654 contributions. The streamwise turbulence intensity  $\frac{\sqrt{u'^2}}{U_{max}}$   
 655 for the fluidic plane WJ shows theoretically two intensity  
 656 peaks: one in the outer flow for a ratio  $\frac{z^*}{z^*_{\frac{1}{2}}}$  equal to 0.7

657 and one in the inner layer, very close to the wall for a ratio  
 658 equal to 0.03. Due to the low PIV resolution near the  
 659 wall this second peak is not spatially resolved and not visible.  
 660 All the profiles show a lower turbulence intensity than  
 661 the fluidic plane WJ. Only the profiles at the end of the  
 662 diffusion zone seem to reach the fluidic plane WJ profile  
 663 (turbulence in the streamwise direction) or are the closest  
 664 to it (turbulence in the normal direction). However, the  
 665 turbulence peak at the end of the diffusion zone is located  
 666 at roughly the same ordinates  $\frac{z^*}{z^*_{\frac{1}{2}}}$  as the theoretical fluidic  
 678

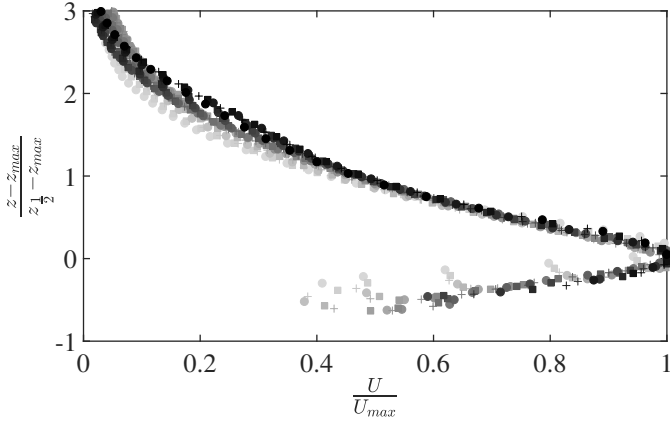
667 WJ as reported in table 4. The value of turbulence in-  
 668 creases in the streamwise direction  $x$  for the three plotted  
 669 stresses indicating that mixing and turbulence production  
 670 increase in the  $x$ -direction as the jet develops and diffuses.  
 682

671 All the turbulence intensity profiles of the curved DBD-  
 672 WJ (figure 15) show a higher turbulence magnitude than  
 673 the fluidic plane WJ as mentioned in Neuendorf and Wyg-  
 674 nanski (1999), in particular for turbulence intensity in the  
 675 streamwise direction. Turbulence enhancement is due to  
 687

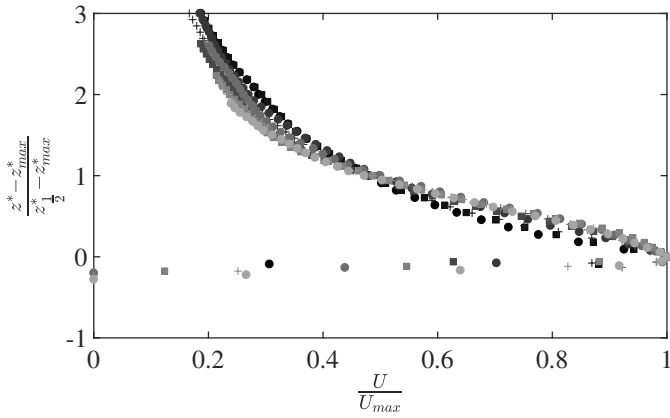
	$\frac{\sqrt{u'^2}}{U_{max}}$	$\frac{\sqrt{v'^2}}{U_{max}}$	$\frac{\sqrt{u'v'}}{U_{max}}$
Wyganski turbulent WJ	0.7	0.7	0.7
Plane DBD (end of the diffusion zone)	0.65	0.9	0.8
Curved DBD (end of the diffusion zone)	0.65	0.65	0.65

Table 4: Ordinates of turbulence intensity peaks

centrifugal forces acting on the jet that generates large ed-  
 dies entraining the external air and inducing a broadening  
 of the DBD-WJ. The ordinates of the maximum intensi-  
 ties are also shown in table 4. This ordinate increases  
 progressively and stabilizes at a value of 0.65 for the three  
 turbulence intensities plotted, remaining not very far from  
 the 0.7 of the fluidic plane WJ. The level of turbulent fluctu-  
 ations tends to increase up to a certain abscissa and then  
 decreases. It is mainly visible for the normal component of  
 turbulence and for the Reynolds stresses. This behaviour  
 evidences the high jet spread and diffusion along the normal  
 direction. However, it is clear that self-similarity of



(a) Plane DBD (diffusion zone)



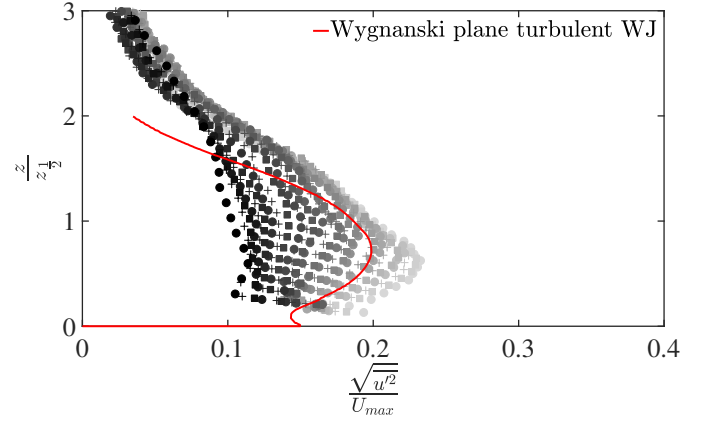
(b) Curved DBD (Pos. C - diffusion zone)

Figure 13: Normalised velocity profiles at different  $x^*$  positions (scaling based on  $z_{1/2}^*$ ,  $z_{max}^*$  and  $U_{max}$ )

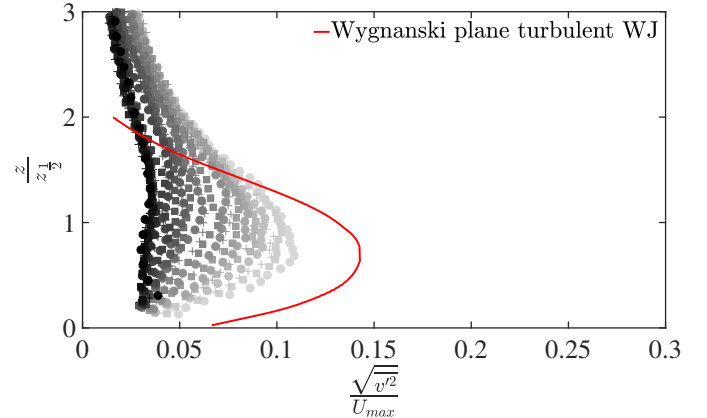
688 turbulence intensity profiles is not obtained with this scaling  
 689 and will not be obtained because of the noticeable  
 690 decline in the turbulent components. This result was in-  
 691 deed expected because self-similarity of the mean flow is  
 692 not completely obtained. However, the analysed veloc-  
 693 ity profiles are very close to the virtual origin (5 virtual  
 694 slot widths for the curved DBD-WJ and 20 for the plane  
 695 DBD-WJ) and these distances are not enough to properly  
 696 characterise a WJ. Wygnanski et al. (1992) found self-  
 697 similarity for the mean velocity profiles of their fluidic WJ  
 698 but did not find it for the turbulent fluctuations with scaling  
 699 1. The authors conducted the experiments up to 120  
 700 slot widths downstream of the nozzle and admitted that  
 701 this distance was not sufficient to attain self-similarity in  
 702 their range of Reynolds numbers. Wilson and Goldstein  
 703 (1976) in their study on the WJ around a cylinder did  
 704 not find self-preservation of the turbulent quantities either,  
 705 even though the mean flow appeared to be quasi-similar.

#### 706 4.3. Transition to turbulence

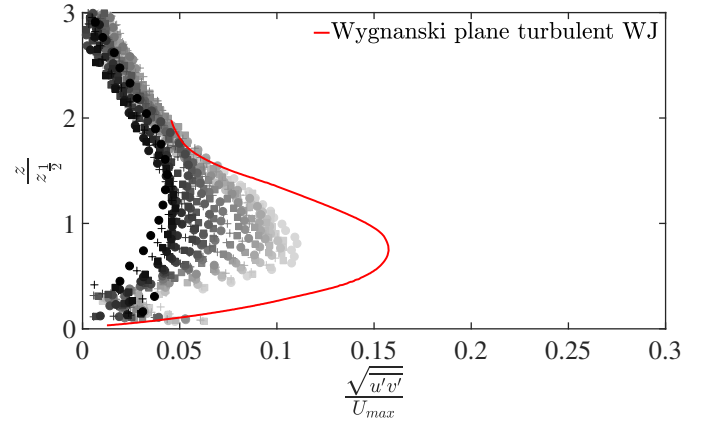
707 The transition to turbulence of the induced jets is ex-  
 708 amined below regarding the DBD set-up and the possible  
 709 flow instabilities.



(a) Turbulence intensity in the streamwise direction



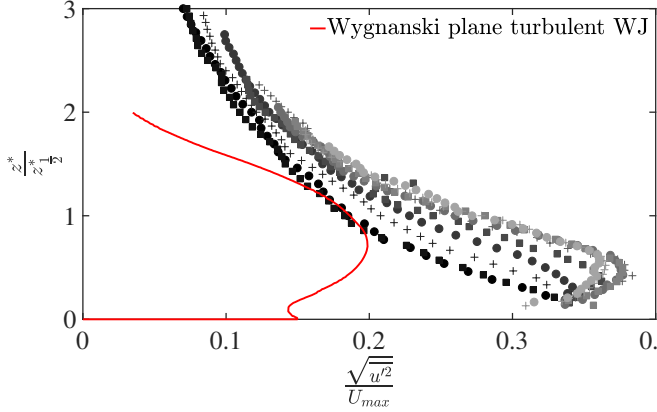
(b) Turbulence intensity in the normal direction



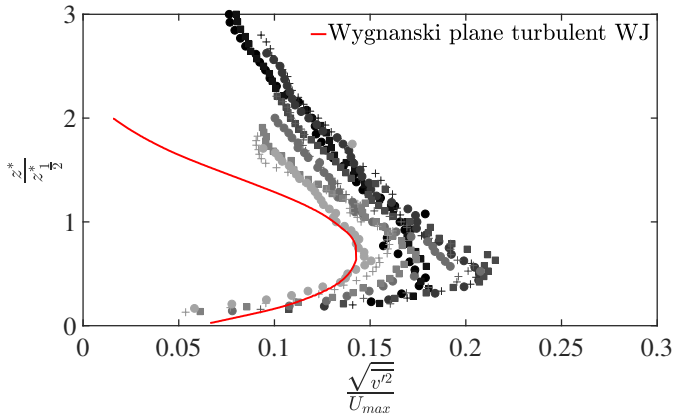
(c) Reynolds stresses

Figure 14: Turbulence intensities and Reynolds stresses at different  $x$  positions based on scaling 1 (plane DBD - diffusion zone)

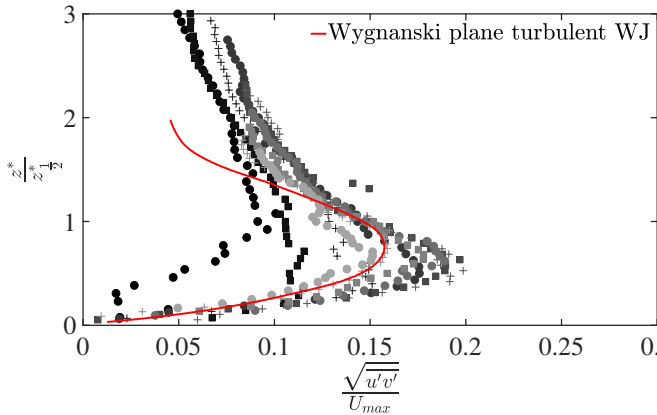
Due to its sinusoidal nature, the DBD actuation produces a local unsteady force resulting from the distinct discharge regimes of positive and negative half cycles. Cohen et al. (1992) studied the laminar to turbulent transition of plane WJs and highlighted two unstable modes: an inviscid mode in the outer region driven by large spatial scales and a viscous mode characterised by small scale



(a) Turbulence intensity in the streamwise direction



(b) Turbulence intensity in the normal direction



(c) Reynolds stresses

Figure 15: Turbulence intensities and Reynolds stresses at different  $x^*$  positions based on scaling 1 (curved DBD - diffusion zone)

disturbances in the inner region. At a distance from the nozzle of 15 slot widths and a  $Re_j = 725$ , these two modes have a reduced frequency  $k = \frac{2\pi f z_{\frac{1}{2}}}{U_{max}}$  equal to 0.7 (inviscid) and 1.25 (viscous),  $f$  being the frequency of the instability. These values correspond to 56 Hz and 99 Hz respectively in the case of the plane DBD-WJ of the present study powered at  $V_{AC} = 18$  kV. These natural instabilities of the present DBD induced jet have very low frequencies com-

pared to the frequency of the actuation equal to 1 kHz. Therefore, it can be considered that, with the actuation, a quasi-steady momentum is produced and that the influence of the natural actuation unsteadiness  $f_{AC}$  on the laminar to turbulent transition is minor.

In addition to shear instabilities, shear flows over concave (or convex) walls are also subjected to an inviscid centrifugal instability quantified by the Rayleigh criterion that imposes  $\frac{1}{r^3} \frac{d}{dr} (r^4 \omega^2) > 0$  as a necessary and sufficient condition for stability. This instability generates streamwise oriented counter-rotating vortices, named Görtler vortices, that can lead the flow to transition to turbulence. This vortex motion is induced by the imbalance between the radial pressure gradient and the centrifugal force. As DBD-WJs have a non-monotonic velocity distribution of the velocity profiles, only the outer part of the WJs is unstable with respect to this centrifugal instability as mentioned in Floryan (1986) and Saric (1994). The calculation of the Görtler number  $G = \frac{U_j \theta}{\nu} \left(\frac{\theta}{R}\right)^{\frac{1}{2}}$ , where  $\theta$  is the jet momentum thickness and  $R$  the radius of curvature of the surface gives, at the virtual origin,  $G \approx 300-350$  for curved actuators leading to an unstable flow as reported in Floryan (1991). Regarding shear and considering the jet Reynolds numbers, DBD-WJs appear to be in a transitional regime whereas for centrifugal instabilities the induced flows are clearly unstable. Therefore, it can be assumed that Görtler instabilities are the primary instability mechanism of curved DBD induced flows.

Furthermore, the used serrated electrodes, which allow higher induced velocities than linear electrodes, generate small vortical structures with a lengthscale equal to the tooth spacing that convect downstream of the DBD-WJ and that locally modify the topology of the induced jets in the very vicinity of the active electrode. However, these structures are convected and dissipated beyond the electrodes and no well-established counter rotating vortices are formed (Joussot et al. (2013)) in the DBD-WJ inner layer where stabilising viscous effects exist. This spanwise forcing may be a factor for the existence of Görtler instabilities but the present PIV data cannot provide the means to address the transverse characteristics of the flow.

#### 4.4. Jet evolution with dimensional variables

Four variables are used in this section to describe the DBD induced WJs evolution along the streamwise  $x$ -direction. The actuators are powered at a voltage  $V_{AC} = 18$  kV and a frequency  $f_{AC} = 1$  kHz. Figure 16a shows the evolution of  $z_{max}^*$  with  $x^*$  and figure 16b plots the evolution of  $z_{\frac{1}{2}}^*$  with  $x^*$ . All the following variables are plotted with respect to the virtual origin  $x_0^*$ , the abscissa where the local jet velocity is maximal, meaning that  $x^* - x_0^* > 0$  corresponds to the jet diffusion zone. In the case of the plane DBD-WJ, a polynomial fitting is performed in the diffusion zone to address the low PIV resolution in the vertical direction. The three zones that distinguish a DBD induced jet can be identified. Aspiration is characterised

780 by a decrease of  $z_{max}^*$  and  $z_{\frac{1}{2}}^*$ . The acceleration zone cor-813  
 781 responds to an almost constant  $z_{max}^*$  located very close814  
 782 to the wall and a progressive increase of  $z_{\frac{1}{2}}^*$  revealing the815  
 783 induced WJ spread. Finally, after the virtual origin the816  
 784 jet does not accelerate anymore, becomes thicker, and dif-  
 785 fuses along the model wall. This generates a progressive  
 786 increase in  $z_{max}^*$  and consequently an increase in  $z_{\frac{1}{2}}^*$ .

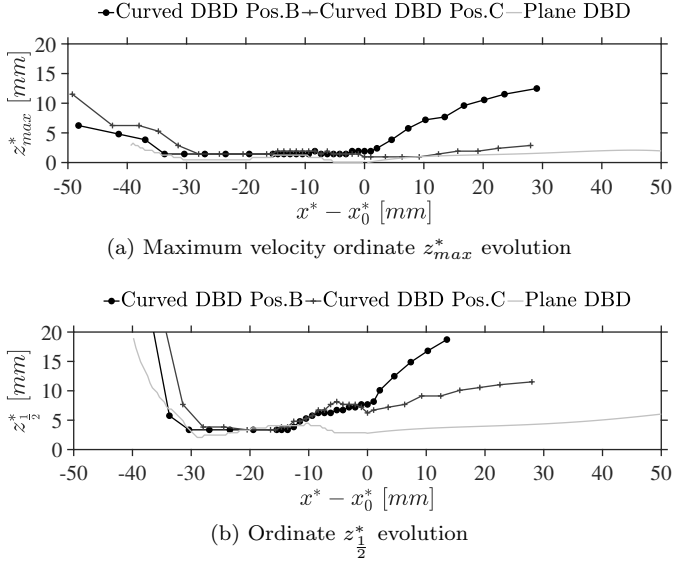


Figure 16: Maximum velocity ordinate  $z_{max}^*$  and ordinate  $z_{\frac{1}{2}}^*$  evolution in the flow direction  $x^*$

787 Due to the detached topology of the induced jet in *Pos.*  
 788 *B*,  $z_{max}^*$  moves away from the wall right after the virtual  
 789 origin. However, both the plane DBD-WJ and the curved  
 790 DBD in *Pos. C* show a similar evolution of  $z_{max}^*$  especially  
 791 in the diffusion zone. For these two attached jets, the ac-  
 792 tuator geometry, plane or curved, does not interfere in the  
 793 ordinate of the maximum velocity that is close to 2.5 mm  
 794 at the end of the diffusion zone actually visible in the PIV817  
 795 field of view. Regarding the evolution of the  $z_{\frac{1}{2}}^*$  ordinate,818  
 796 curved DBD-WJs prove to have a higher spread than the819  
 797 plane one reaching 10 mm and 20 mm when their plane820  
 798 equivalent reaches 7 mm at the end of their respective dif-821  
 799 fusion zones. The induced jet in *Pos. B* reveals a spread822  
 800 that is twice as high as the one in *Pos. C* that is itself two823  
 801 times greater than the corresponding plane configuration.824  
 802 This evolution is in reasonable agreement with the results825  
 803 obtained by Bradshaw and Gee (1960) who found that the826  
 804 spread of a fluidic WJ over a cylinder is 1.5 times higher827  
 805 than over a flat plate.828

806 Local maximum velocity  $U_{max}(x^*)$  in the streamwise di-829  
 807 rection  $x^*$  is plotted in figure 17a. By definition, the ve-830  
 808 locity decay appears for all the actuators just beyond the831  
 809 virtual origin  $x_0^*$ . The maximum velocity is of the same832  
 810 order of magnitude for the three actuators plotted but the833  
 811 velocity decay is slower for the plane DBD-WJ. For this834  
 812 jet, the multi-DBD actuation is clearly visible as the veloc-835

ity increases in two stages: a first stage up to 1.8 m/s and  
 a second stage up to 3.3 m/s. A two-step velocity increase  
 is also visible for the curved flows whose velocity gap be-  
 tween the two single-DBDs is about 0.5 m/s to 1 m/s.

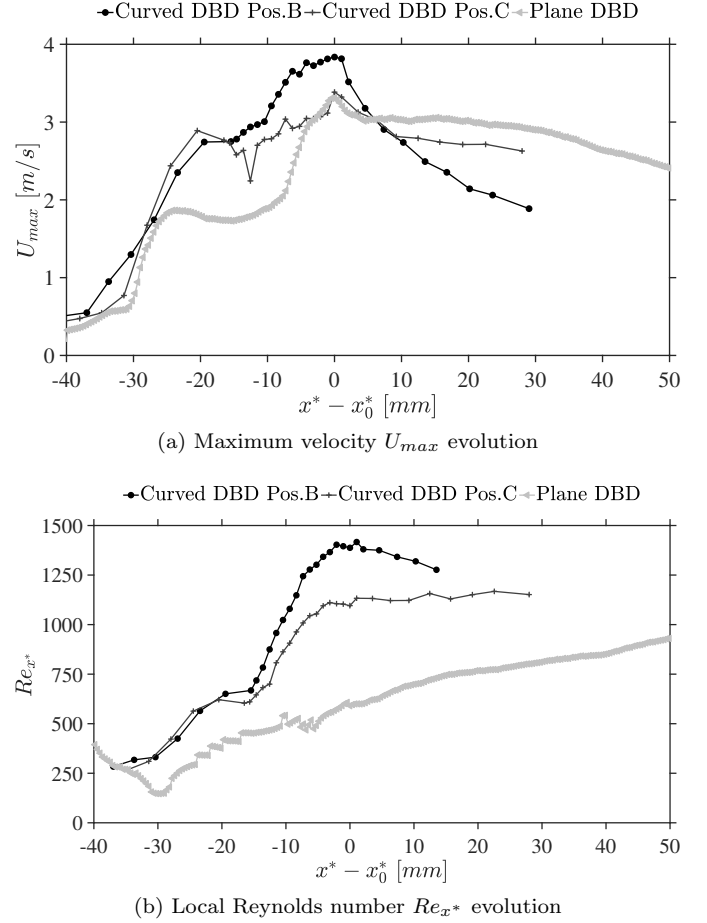


Figure 17: Maximum velocity  $U_{max}$  and local Reynolds number  $Re_{x^*}$  evolution in the flow direction  $x^*$

The evolution of the local Reynolds number  $Re_{x^*}$  with  
 $x^*$  is shown in figure 17b. In the case of the plane DBD-  
 WJ, the increase in the Reynolds number begins over the  
 first actuator ( $x^* - x_0^* \in [-30, -20]$ ) and  $Re_{x^*}$  continues  
 to grow past the virtual origin at a relatively constant pace.  
 This happens because the spread is greater than the veloc-  
 ity decay in the diffusion zone inducing a  $Re_j$  increase up  
 to 900. The curved DBD-WJ in *Pos. B* shows a slight de-  
 crease after the virtual origin because its velocity decrease  
 is greater than the rate of spread increase. The curved  
 DBD-WJ in *Pos. C* shows a Reynolds number plateau  
 in the diffusion zone. For both curved jets, the Reynolds  
 number increases in two distinct steps that again highlight  
 the implementation of multi-DBD actuators. Because of  
 the greater thickness of curved DBD-WJs, their overall  
 $Re_{x^*}$  level is greater than for the plane DBD induced jet.

The electrode arrangement is identical for the three ac-  
 tuators studied, the only distinct parameter is the geome-  
 try of the actuator basis (curved or plane) and the position

836 of the electrodes around the curvature when the surface is  
 837 curved. These results suggest that there is an effect of the  
 838 surface curvature on the jet development specially in terms  
 839 of rate of spread that more than doubles for the curved jet  
 840 compared to its plane equivalent.

#### 841 4.5. Jet evolution with normalised variables

842 A wall jet development over a surface can be character-  
 843 ised by the evolution of two main parameters: the  
 844 maximum velocity decay and the rate of spread. The  
 845 three scaling laws explained in table 2 were applied to  
 846 the present experimental data in order to characterise the  
 847 streamwise evolution of DBD induced jets in the diffusion  
 848 zone solely. Concerning scaling 1 and as pointed out by  
 849 Förthmann (1936), the decay of the maximum jet velocity  
 850 is expected to vary as  $x^{-\frac{1}{2}}$ . In order to accentuate  
 851 the decay, the ratio  $\left(\frac{U_j}{U_{max}}\right)^2$   
 852 sus  $\frac{x^* - x_0^*}{b^*}$  and is shown in figure 18a for the diffusion  
 853 zone only i.e.  $x^* - x_0^* > 0$ . Figure 18b shows the rate of  
 854 spread in the streamwise direction i.e.  $\frac{z_{\frac{1}{2}}^*}{b^*}$  as a function of  
 855  $\frac{x^* - x_0^*}{b^*}$ . Maximum velocity decay and rate of spread can  
 856 be expressed by the following power laws (equations 6 and  
 857 7 respectively) where  $A_u$  and  $A_z$  are constants summarised  
 858 in table 5.

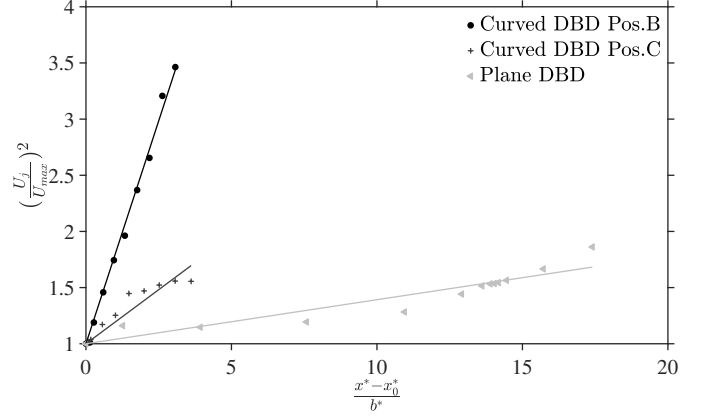
$$\left(\frac{U_j}{U_{max}}\right)^2 = A_u \left(\frac{x^* - x_0^*}{b^*}\right) \quad (6)$$

$$\frac{z_{\frac{1}{2}}^*}{b^*} = A_z \left(\frac{x^* - x_0^*}{b^*}\right) \quad (7)$$

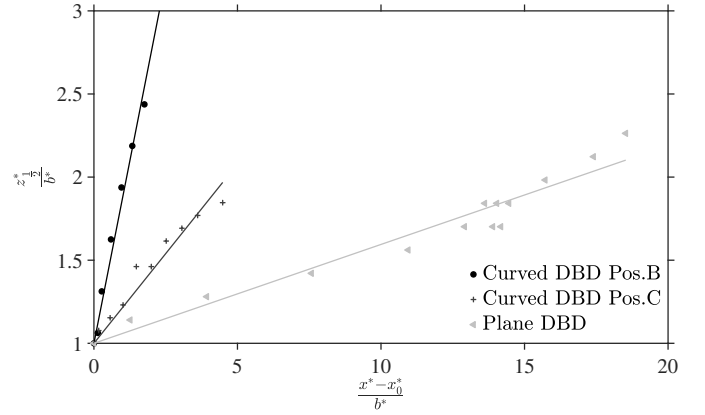
	$Re_j$	$A_u$	$A_z$
Curved DBD Pos. B	1900	0.80	0.87
Curved DBD Pos. C	1300	0.19	0.22
Plane DBD	600	0.04	0.06
Wynanski et al. (1992)	3400	0.15	0.09

Table 5: Table summarizing slope values  $A_u$  and  $A_z$  of the power laws in equations 6 and 7

859 After the virtual origin  $x_0^*$ , the evolution of  $\left(\frac{U_j}{U_{max}}\right)^2$   
 860 is linear for both curved and plane DBD-WJs confirming  
 861 the theoretical  $x^{-\frac{1}{2}}$  evolution of the velocity decay. In  
 862 the same way, the rate of spread of DBD induced jets  
 863 behaves as a classical fluidic WJ and evolves linearly in  
 864 the diffusion zone. DBD curved WJs exhibit a much higher  
 865 velocity decay than the plane DBD and a higher rate of  
 866 spread as well. The effect of the jet Reynolds number is  
 867 significant in the present study. The higher the  $Re_j$ , the  
 868 higher the slopes  $A_u$  and  $A_z$ . For instance, the slopes of



(a) Max. velocity decay



(b) Rate of spread

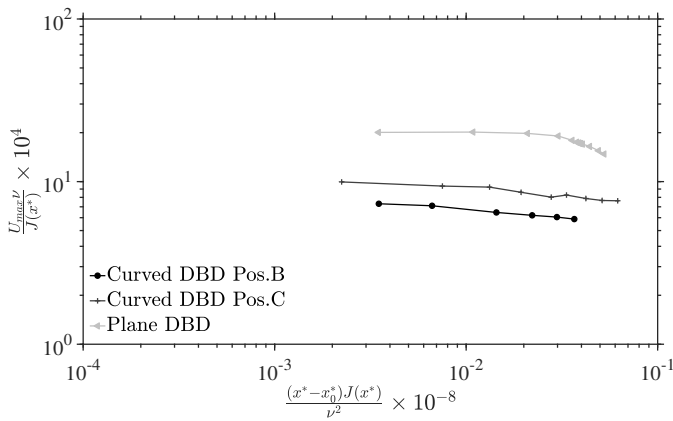
Figure 18: Maximum velocity decay and rate of spread in the flow direction based on scaling 1 (diffusion zone)

869 the actuator in *Pos. B* are more than 10 times higher  
 870 than the ones concerning the plane WJ. There is, indeed,  
 871 a Reynolds number effect arising from the jet thickness  $b^*$ ,  
 872 itself directly related to the electrode position around the  
 873 TE and to the jet topology. This  $Re_j$  evolution is not in  
 874 agreement with the results obtained by Wynanski et al.  
 875 (1992) who found an opposite behaviour for a classical  
 876 fluidic plane WJ. However, DBD induced jets are different  
 877 in nature to purely fluidic ones and comparisons should be  
 878 made carefully.

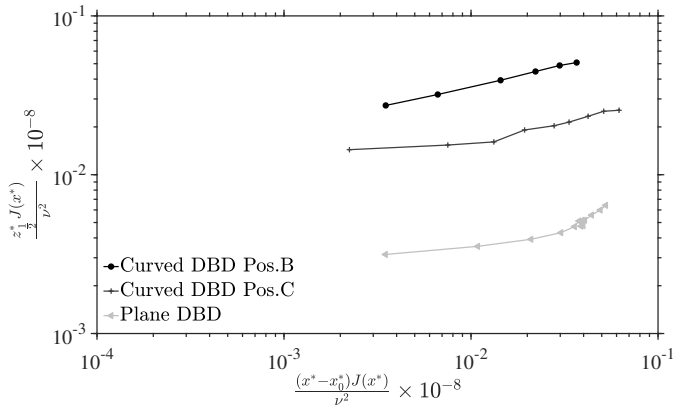
879 A second scaling involving the kinematic momentum  
 880 flux  $J$  and the kinematic viscosity  $\nu$  (scaling 2) is intro-  
 881 duced. This scaling arises from Narasimha et al. (1973)  
 882 who suggested that a fully developed WJ should attain an  
 883 equilibrium independent of the nozzle conditions (such as  
 884  $b^*$ ) and only dependent on the kinematic momentum flux  
 885 at the nozzle  $J_0$ . As self-similarity of the mean flow is  
 886 not completely reached in the present study, scaling 2 was  
 887 used with the local momentum flux  $J(x^*)$ . The same plots  
 888 with a scaling based on  $J_0$  do not add any supplementary  
 889 information to the analysis. The corresponding scaling  
 890 values for the velocity decay and rate of spread evolution



891 are  $\frac{U_{max}\nu}{J(x^*)}$  and  $\frac{z_{\frac{1}{2}}^* J(x^*)}{\nu^2}$ , whereas the streamwise direction<sup>912</sup>  
 892 evolves as  $\frac{(x^*-x_0^*)J(x^*)}{\nu^2}$ . Figures 19a and 19b show the<sup>913</sup>  
 893 velocity decay and the rate of spread respectively in the<sup>914</sup>  
 894 streamwise direction. All the plotted experimental points<sup>915</sup>  
 895 correspond to the diffusion zone of the induced WJs. Scal-<sup>916</sup>  
 896 ing 2 does not collapse the streamwise behaviour of the<sup>917</sup>  
 897 three DBD induced jets. Evolutions of the rate of spread<sup>918</sup>  
 898 and of the maximum velocity decay are roughly linear and<sup>919</sup>  
 899 their slopes are not very far from each other. However,<sup>920</sup>  
 900 the three curves are not superimposed, implying that the<sup>921</sup>  
 901 kinematic momentum flux is not a valid parameter for the<sup>922</sup>  
 902 normalisation of DBD-WJs evolution. The curves suggest<sup>923</sup>  
 903 that the kinematic momentum flux is not the only param-<sup>924</sup>  
 904 eter that drives the jet spread and velocity decay.



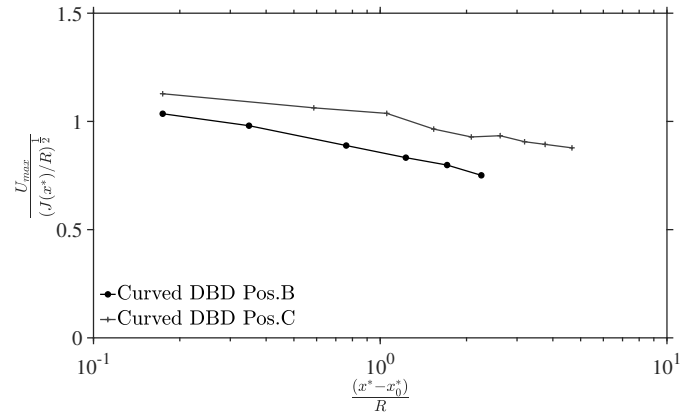
(a) Max. velocity decay



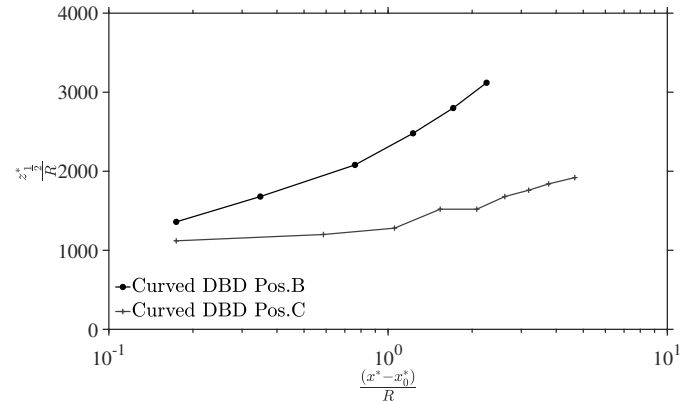
(b) Rate of spread

Figure 19: Maximum velocity decay and rate of spread in the flow direction based on scaling 2 (diffusion zone)

of the velocity decay and  $\frac{z_{\frac{1}{2}}^*}{R}$  in figure 20b for the evaluation of the rate of spread. The evolution of these variables is plotted as a function of  $\frac{(x^*-x_0^*)}{R}$ . This scaling collapses the two curves for the velocity decay reasonably well, suggesting that the radius of curvature is an important length scale of the curved DBD-WJs even in the diffusion zone and after the effective curvature. The scaling seems less relevant for the characterisation of the rate of spread evolution, since the actuator in *Pos. B* shows a greater spread than the one in *Pos. C* with this normalisation as well. However, for both jets, the rate of spread seems to follow a square evolution.



(a) Maximum velocity decay



(b) Rate of spread

Figure 20: Maximum velocity decay and rate of spread in the flow direction based on scaling 3 (diffusion zone)

## 5. Conclusion

The present work dealt with transitional DBD induced jets developing over curved surfaces and studied in the framework of an experimental circulation control application, carried out by acting near a rounded trailing-edge of an airfoil. The same DBD configuration was employed on a plane configuration and on three curved configurations where the electrodes were placed along the rounded trailing-edge.

905 A third scaling suggested by Neuendorf and Wygnanski<sup>925</sup>  
 906 (1999) for the wall jet developing around a circular cylinder<sup>926</sup>  
 907 and involving the radius of curvature  $R$  (scaling 3) was<sup>927</sup>  
 908 used. Indeed, when the ratio  $\frac{b^*}{R}$  is not small the length<sup>928</sup>  
 909 scale  $R$  has real meaning. In the present investigation,<sup>929</sup>  
 910  $b^*$  is of the same order of magnitude as  $R$ . In this way,<sup>930</sup>  
 911  $\frac{U_{max}\nu}{J(x^*)}$  is plotted in figure 20a for the characterisation<sup>931</sup>  
 912

Time averaged velocity fields from PIV measurement in quiescent air conditions allowed to assess the evolution of these flows. Firstly, they show that the electrode position around the curvature has a direct impact on the jet topology and particularly on whether the induced jet is going to follow the model curvature or not. The configuration where the zone of EHD interaction reaches the end of the curvature allows a complete adhesion of the induced jet to the wall. The reason why the wall jet stays attached to the wall seems to be more an electrical effect than a phenomenon due to the dynamics of the fluid. A possible Coanda effect is not applicable in this study as the Reynolds numbers of the induced jets are small and the jet thicknesses are large compared to the common cases of jet adhesion to a curved surface. Secondly, compared to plane DBD wall jets, curved DBD wall jets experience centrifugal effects. Wall curvature induces higher wall jets thicknesses and rates of spread in the diffusion zone leading to an important entrainment of the outer flow. Such as for fluidic wall jets along a cylinder the radius of curvature of the wall is an important length scale to describe the DBD wall jet evolution, more particularly with regard to the velocity decay. Compared to plane DBD wall jets in which shear instabilities drive the transition mechanism, it seems that, for curved DBD wall jets, transition is likely triggered by the centrifugal instabilities taking place especially in the outer jet area. When comparing the main features of DBD wall jets in the diffusion zone to canonical fluidic wall jets, plane and curved DBD induced jets show a similar velocity decay and rate of spread evolution in the streaming direction expected to vary as  $x^{-\frac{1}{2}}$  and linearly respectively. Regarding the self-similarity of the mean velocity profiles along the streaming direction, a quasi-similarity can be observed in the diffusion zone but self-similarity of the turbulent components is not obtained and cannot be obtained because of the noticeable and quick decline of the fluctuation components before the jet dissipation or separation. Indeed, due to their inherent limitation to produce high velocity flows, the jet Reynolds numbers of DBD wall jets remain very low, in the range of laminar or transitional jets, compared to the common Reynolds numbers of fluidic wall jets. Thus, it can be assumed that DBD cannot induce fully developed turbulent jets. Conducting this study in the presence of an external flow would probably reveal other aspects of the evolution properties of DBD wall jets, as for fluidic wall jets. This approach remains a challenge as discussed in Pereira et al. (2014), more particularly to consider accurately the wall shear changes.

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