

1 **Numerical optimization and experimental validation for a**
2 **tidal turbine blade with leading-edge tubercles**

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17 **Abstract:** Recently the leading-edge tubercles on the pectoral fins of humpback whales have
18 attracted the attention of researchers who wish to exploit this feature in the design of turbine
19 blades to improve the blade performance. The main objective of this paper is therefore to make
20 a further investigation into this biomimetic design inspiration through a fundamental research
21 study involving a hydrofoil section, which represents a straightened tidal turbine blade, with
22 and without the leading-edge tubercles, using computational and experimental methods.

23 Firstly a computational study was conducted to optimise the design of the leading-edge
24 tubercles by using commercial CFD code, ANSYS-CFX. Based on this study the optimum
25 tubercle configuration for a tidal turbine blade with S814 foil cross-section was obtained and
26 investigated further. A 3D hydrofoil model, which represented a “straightened” tidal turbine
27 blade, was manufactured and tested in the Emerson Cavitation Tunnel of Newcastle University
28 to investigate the effect of various tubercle options on the lift and drag characteristics of the
29 hydrofoil. The experiments involved taking force measurements using a 3-component balance
30 device and flow visualisation using a Particle Image Velocimetry (PIV) system. These tests
31 revealed that the leading-edge tubercles may have significant benefits on the hydrodynamic
32 performance of the hydrofoil in terms of an improved lift-to-drag ratio performance as well as
33 reducing the tip vortex which is main cause of the undesirable end-effect of 3D foils. The study
34 explores further potential benefits of the application of leading-edge tubercles on tidal turbine
35 blades.

36 **Keywords:** Tidal turbine, Leading-edge tubercle, Foil tests, Computational Fluid Dynamics
37 (CFD), Lift and drag measurements, Flow visualisations, Particle Image Velocimetry (PIV)

38 **1 Introduction**

39 The humpback whale is a species of giant marine mammal, ranging from 12~16m long. In spite
40 of its large size this creature is unique in its ability to do athletic manoeuvres, especially in
41 catching its prey, compared to other similarly sized marine mammals. Humpback whales utilize
42 their unusually long pectoral fins to perform tight turns to drive a school of fish into a small
43 circular zone so that they can swallow their prey all together. Close observation of their long
44 fins indicates that the leading edges of these fins are not smooth, having some tubercles which
45 are round shape protuberances [1, 2]. Wind tunnel tests showed that placing leading-edge
46 tubercles on foils could improve the foil performance in terms of delayed stall and higher lift-
47 to-drag ratio [3-8].

48 A number of numerical and experimental investigations has been conducted to understand the
49 tubercle concept [8-12]. Some of these investigations indicated that the effects caused by the
50 tubercles on the performance of a 2 dimensional (2D) foil and 3 dimensional (3D) foil are quite
51 different [3, 5, 6, 9, 11, 13-15]. Studies on the 2D foils were more focused on the optimisation
52 of the sinusoidal shape tubercle profiles defined by different parameters. Optimised tubercle
53 profiles on these 2D sections could improve the lift coefficient curves further by maintaining
54 the lift after the stall point. However this was at the cost of a reduction in the maximum lift
55 coefficients since the drag coefficients were increased by these tubercles, at the same time. On
56 the other hand, different performance characteristics have been reported based on the
57 investigations with the leading-edge tubercles on 3D foils which are usually tip tapered like
58 rudders, stabilizer fins, wings, flippers etc. The investigations with the 3D foils also claim the
59 improvement of the lift coefficient curves by maintaining the lift beyond the stall point which
60 is similar to the effect of tubercles on 2D foils. However, in addition to this, the performance
61 regarding to the lift-to-drag ratio can be enhanced [6-8, 11, 16, 17].

62 Encouraged by the previous investigations into tubercle performance, especially for the 3D foil
63 applications, an attempt was made recently to apply the tubercle concept to tidal turbine blades
64 and scaled turbine models with different tubercle designs were tested in a towing tank [18].
65 Some performance improvement was demonstrated in this application even though the power
66 coefficients achieved were not comparable to state-of-the-art levels due to various design and
67 other issues developed during the tests. The blade with only a 1/3 of the span covered with
68 tubercles displayed the best performance amongst the different ranges of the tubercle
69 extensions over the blade span. Based on the results of this recent research it was thought that,
70 there was a scope for further research and development in this field to improve the performance
71 of a tidal turbine and demonstrate it in a validated manner.

72 The main objective of this study is therefore to make a further contribution to the understanding
73 of the tubercle concept in the design of tidal turbine blades by using computational and
74 experimental approaches. Within this framework, a fundamental investigation using a single
75 2D and 3D blade configuration is presented in this study. This is intended to achieve some
76 basic understandings of the leading-edge tubercles on a straightened turbine blade prior to
77 applying them to the real blades of a whole tidal turbine.

78 In the remainder of this paper, an optimization study is presented in Section 2 to optimise the
79 main parameters of the leading-edge tubercles for a single blade with S814 cross-section profile
80 by using the commercial CFD software, ANSYS-CFX. In this exercise a reference 2D foil

81 fitted with different sizes of tubercles was analysed to lead on to the design of a 3D foil with
82 tubercles. Then a straightened 3D foil based on a tidal turbine blade with the same chord length
83 distribution but with a constant pitch angle was designed by using the optimised tubercles and
84 a physical model based on this design was tested in a cavitation tunnel as presented and
85 discussed in Section 3 of the paper. Finally main conclusions obtained from the study are
86 presented in Section 4.

87 **2 Tubercle Design and Optimization**

88 **2.1 Description of Tubercle Design**

89 The design study was based on a previous UK National research programme (EPSRC-RNET),
90 in which a tidal turbine was designed based on the S814 profile cross-section from the NREL
91 series, as shown in Figure 1 from Wang et al [19] who conducted an experimental investigation
92 into the efficiency, slipstream wash, cavitation and noise characteristics of this turbine. The
93 scaled turbine model is shown in Figure 2 as mounted on the open water dynamometer of the
94 Emerson Cavitation Tunnel of Newcastle University. A representative and straightened version
95 of this turbine blade, which is based on the S814 profile cross-section, was considered as the
96 reference foil in this study to apply the tubercle concept.

97 The investigation into the optimisation of the tubercle profiles was initiated by systematically
98 changing the Height (H) and the Wavelength (W) of these protrusions based on the sinusoidal
99 form of their shapes. Two sets of tubercle designs were simulated with two different heights
100 which were assumed 5% and 10% of the foil chord length (C) and combined with ten
101 wavelength arrangements varying from 0.1C to 1C in 0.1C increments. The definitions of these
102 parameters are shown in Figure 3.

103 **2.2 Numerical Method and Validation**

104 Before investigating the effect of the designed tubercles on the foil performance, the foil test
105 data available from Ohio State University was used to validate the CFD model [20, 21].
106 According to the previous 2D foil studies [5, 6, 8, 11], the tubercles were found to be beneficial
107 when the foil was under stall or near stall conditions. However the simulation of a foil
108 performance under stall conditions was a challenging case in CFD simulations [22, 23].
109 Therefore the establishment of a reliable CFD model, in terms of the turbulence modelling,
110 effective mesh generation, etc., would be critical for the simulations as discussed in the next.

111 **2.2.1 Turbulence Model**

112 For the optimisation study presented here, a more computationally economical time
113 independent steady state RANS model was preferred. Industrially acknowledged and
114 recommended K-epsilon and Shear Stress Transport (SST) turbulence models were
115 investigated in the study [23].

116 **2.2.2 Mesh Generation**

117 Mesh quality for curved surfaces is another critical issue for CFD simulations. As a first attempt
118 a structured mesh of around 1 million O-type elements was generated by the ANSYS-

119 MESHING module [23]. The value of the non-dimensional wall parameter, y^+ , was kept as 1
120 to ensure the required mesh quality within the boundary layer [22] and the growth ratio was
121 limited to 1.08. The outer boundary was set at about 10 chord lengths away from the foil.
122 Meanwhile newly developed Solution Adaptive Mesh technology was also used to adapt the
123 mesh automatically based on the flow gradient [23]. This enabled more effective mesh
124 distribution depending on the requirements.

125 Figure 4 shows the whole mesh and the details of the grid near the foil section before the
126 solution adaptive mesh was processed. However after the process of solution mesh adaption,
127 the number of elements became around 2.5 million or more which depended on the calculation
128 cases. The mesh would be further refined automatically during the simulation itself, as shown
129 in Figure 5.

130 **2.2.3 Validation of CFD**

131 Figure 6 shows the comparison of the CFD predictions for the experimental lift and drag
132 coefficients of the Ohio State University foil. The CFD simulations were conducted using both
133 K-epsilon and SST turbulence models by maintaining the chord length based Reynolds number
134 at 10^6 . As shown in Figure 6, both CFD simulations with the two different turbulence models
135 displayed very good agreement with the experiments up to a 10 deg of angle of attack (AOA)
136 where the stall occurred. After the stall, the CFD predictions overestimated the lift coefficient
137 especially using the K-epsilon turbulence model. However, when the CFD simulation with the
138 SST turbulence model was combined with the solution adaptive mesh technique [22] the
139 prediction was greatly improved, as shown in Figure 6. Similar comparisons are also shown
140 for the drag coefficients. As shown in Figure 6, the predictions with the SST turbulence model
141 combined with the solution adaptive technique show close agreement with the experimental
142 data. Finally, the comparisons of the CFD predictions with the experimentally measured
143 pressure distribution around the foil in stall condition are shown in Figure 7 and Figure 8 and
144 again display very good correlations. Therefore the SST turbulence model with the solution
145 adaptive mesh was adopted for the analysis of the flow.

146 **2.3 Optimization Result and Analysis**

147 Using the validated CFD model, the lift coefficients of the foil with the S814 profile cross-
148 section and sinusoidal tubercles of differing parameters were simulated. As shown in Figure 9
149 and Figure 10, the tubercles on 2D foils maintained higher lift coefficients in the post-stall
150 region ($20^\circ \sim 40^\circ$) while they also reduced the maximum lift coefficient. Increasing the tubercle
151 wavelengths brought the lift coefficients of the foil with the leading-edge tubercles closer to
152 the lift coefficients of the reference or “baseline” foil with the smooth leading edge i.e. without
153 tubercles. However reducing the wavelengths increased the lift at higher angles of attacks while
154 reducing the maximum value of the lift. By taking into account these trends, the foil having a
155 sinusoidal form of tubercle with the height and wavelength of $H=0.1C$ and $W=0.5C$,
156 respectively, was considered to be a good compromise from the performance point of view and
157 was chosen for further analysis as a 3D foil.

158 Post analysis of the CFD simulation results of the cases, “Baseline” and the optimised “H-0.1,
159 W-0.5”, under 15° are shown in Figure 11. The velocity iso-surfaces for the case where the
160 velocity is equal to 50% of the incoming velocity, reveal the flow separation patterns and were
161 plotted and coloured base on the pressure distribution. As shown in Figure 11, the flow pattern

162 around the foil was favourably affected by the presence of the tubercles as the flow appeared
163 to be more attached to the foil surface following the crest of the tubercles whereas the baseline
164 foil without tubercles displayed separated flow after the leading edge.

165 **3 Foil Design and Test**

166 Having conducted the CFD analysis on the 2D foil and validated the results, the next task was
167 the design of a representative 3D foil with tubercles, based on an existing tidal turbine blade,
168 and to conduct dedicated experiments to investigate the effect of tubercles on the hydrodynamic
169 characteristics of this foil.

170 **3.1 Foil Design and Manufacture**

171 As reported in the open literature [6, 11] by previous researchers the effect of tubercles on the
172 hydrodynamic performance of 2D and 3D foils was different and further evidence supporting
173 this claim would be welcome as one of the natural outcomes of the present study. Therefore a
174 3D foil representing a turbine blade was designed and model tested in this section.

175 As stated in Section 2.1, the representative 3D foil was based on the blade of the tidal turbine
176 designed by Wang et al [19]. However, while the foil had the same chord length distribution
177 as the subject tidal turbine blade it had a constant pitch. Based on the limitations imposed by
178 the testing section of the ECT, the span of the test foil was specified as 560mm. Considering
179 the operating range of the tip speed ratios (TSRs), the range of the angles of attack (AOA) to
180 be applied on the foil during the tests was specified to be 0° to 40° while the inflow velocities
181 were selected as 2, 3 and 4m/s. Over this inflow velocity range, the reference Reynolds number
182 (Re), which was described based on the chord length (150mm) of the foil at 0.7 radius, was
183 varied from 0.3×10^6 to 0.6×10^6 . This was similar to the Re range for the turbine model that was
184 used by Wang et al [19].

185 According to the optimisation task with the 2D foil presented in Section 2.3, the foil with the
186 tubercles would display relatively the best performance when the height (H) and wavelength
187 (W) of the tubercles were $0.1C$ and $0.5C$, respectively. Hence approximately 8 sinusoidal
188 tubercles with successive crests and troughs were evenly distributed along the leading edge.

189 Based on the above arrangement, the 3D foil was manufactured in two separate parts and then
190 assembled. The first part was the interchangeable (or removable) leading-edge part of the foil
191 while the second part was the remainder (i.e. main body) of the foil that also supported the
192 whole foil structure. The interchangeable leading-edge was printed using a 3D printer in four
193 segmented pieces from a liquid resin material, Stratasys Vero White Plus RGD835.

194 The interchangeable and segmented manufacture of the leading-edge profiles provided very
195 useful flexibility for testing the different leading-edge arrangements as well as overcame the
196 size limitation of the 3D printer. The main body of the foil was milled by CNC machine from
197 a carbon fibre reinforced plastic (CFRP) to ensure that the structure would be strong enough
198 and the deformation minimal. All the models with various combinations of the leading edge
199 profiles are shown in Figure 12.

200 The main foil with five different leading-edge combinations, one of which was the smooth
201 leading edge, was tested and corresponding hydrodynamic performances were compared to
202 explore the effect of the four different tubercle arrangements on the foil performance. In order
203 to classify the different leading-edge tubercle combinations, the reference foil with the smooth
204 leading-edge section was represented by legend “0000” while the foil with the leading-edge
205 tubercles covering the whole span was represented by “1111”. Other leading-edge
206 combinations with partial tubercle applications were represented using legend “0001”, “0011”
207 and “0111” for the 1/4, 1/2 and 3/4 coverage of the foil span by the tubercles from tip to root,
208 respectively.

209 **3.2 Experimental Setup**

210 The experiments were conducted in the Emerson Cavitation Tunnel (ECT) at Newcastle
211 University. The tunnel is a medium size propeller cavitation tunnel with a measuring section
212 of 1219mm×806mm (width × height), as shown in Figure 13. The speed of the tunnel inflow
213 varies between 0.5 to 8 m/s. Full details of the ECT and its further specifications can be found
214 in reference [24].

215 The lift and drag performance of the test foil was the primary interest during the experiments
216 as in many foil investigations. During the tests, the forces (X, Y) acting on the foil, which was
217 suspended vertically from the upper lid in the mid-plane of the tunnel measuring section, were
218 measured using a 3-component balance device. This device was a Cussons R102 balance which
219 was specially designed and manufactured for the ECT to be mounted on the top lid of the tunnel
220 using a height and angle adjustment mechanism. The test foil was mounted to the bottom plate
221 of the 3-component balance to transfer the forces to the 3 load cells and a circular plate was
222 fitted at the root of the blade to prevent the tunnel inflow entering into the cavity, where the
223 balance was housed, as shown in Figure 14.

224 The measured lift and drag forces were represented by the following non-dimensional
225 coefficients:

$$C_L = \frac{Lift}{\frac{1}{2}\rho V^2 A} \quad \text{Equation (1)}$$

$$C_D = \frac{Drag}{\frac{1}{2}\rho V^2 A} \quad \text{Equation (2)}$$

226 Where *Lift* is the measured lift of the foil which is perpendicular to the incoming flow; *Drag* is
227 the measured drag of the foil which is aligned with the incoming flow; ρ is the density of the
228 tunnel water, which was measured as 1004 kg/m³ using a density meter; *V* is the tunnel inflow
229 velocity; *A* is the reference area of the foil which is assumed to be equal to the foil projected
230 area, 0.0924 m².

231 All the measured data were gathered by a National Instruments data acquisition system and
232 analysed instantaneously by LabVIEW. For each measurement point, 500,000 samples were

233 acquired at a 1 kHz sample rate and averaged to calculate the mean value. During the
234 experiments, each test run was repeated three times for uncertainty analysis. The average
235 results were then plotted and compared. The maximum values of CL and CD were 2.3% and
236 3.1%, respectively, with mean values of standard deviation of 1.1% and 1.0%, respectively.
237 One example of the uncertainty analysis is presented in Figure 15.

238 In order to measure and analyse the flow field around the foil, a 2D particle image velocimetry
239 (PIV) system was used, while some still photo images were also taken. The detailed technical
240 specification of the PIV system used, which was a Dantec Dynamics Ltd product, is shown in
241 Table 2. During the use of this system, the flow field was illuminated by the planar laser light
242 sheet which was perpendicular to the hydrofoil and highly seeded flow field images were
243 captured by the double framing high-speed CCD camera at a frequency of 500Hz and 0.0004s
244 time interval. Throughout the measurements, 100 double frame image pairs needed to be
245 captured, analysed and averaged to achieve a time-averaged velocity distribution. The adaptive
246 PIV analysis was used for the 2D images from each camera with a grid size of 16x16 pixels.
247 Afterwards, the results of these 100 velocity samples were averaged to achieve the final results.

248 **3.3 Force Measurement Results and Analysis**

249 **3.3.1 Reynolds Number Effect**

250 First of all, based on the above test set-up, the reference foil “0000” was tested at 2, 3 and 4m/s
251 tunnel velocity to demonstrate the effect of Reynolds number (Re). Because of the practical
252 limitations of the testing facility, a typical full-scale Re range for a tidal turbine, which often
253 ranges from 10×10^6 to 30×10^6 based on the chord length at 0.7 radius, could not easily be met
254 within the model scale test. In the current tests, the Re range was varied from 0.3×10^6 to 0.6×10^6
255 where the Re was described based on the reference chord length of 150mm at 0.7 radius. It is
256 important that the Reynolds number effect has to be checked prior to any flow tests and certain
257 precautions must be taken to improve the circumstances for very low Re cases.

258 Figure 16 shows the measured lift, drag and lift-to-drag ratio of the reference foil (i.e. Foil
259 0000) which are represented in terms of the associated coefficients as described in Section 3.2.
260 In this figure the last character with an underscore bar in the legend used refers to the tunnel
261 incoming velocity (e.g. 0000_2, where the tunnel velocity is 2 m/s). As shown in Figure 16,
262 within the range of the Reynolds numbers tested, the slope and maximum value of lift
263 coefficients decrease gradually with increasing Re. On the other hand, the drag coefficients are
264 nearly identical for different values of Reynolds number. Thus, the lift-to-drag ratios of the
265 reference foil with the smooth leading-edge are reduced with increasing Reynolds number.

266 The tests conducted for the reference foil (Foil “0000”) were repeated for Foil “1111” which
267 had full leading-edge tubercles and the results are presented in Figure 17. As shown in Figure
268 17, unlike in the reference foil case, the lift coefficient of the foil with the leading-edge
269 tubercles increases with the Reynolds number, particularly after a 14° angle of attack (AOA)
270 for 2m/s and 3m/s flow speed. A large gap can be seen between the lift coefficients for 2m/s
271 and 3m/s. There seemed to be a trend suggesting that the lift-to-drag ratio can be enhanced with
272 increasing Reynolds number and hence the foil with the leading-edge tubercles may have a
273 better performance at higher range of Reynolds number.

274 3.3.2 Performance Comparison between the Foils with and without Tubercles

275 Figure 18 shows the comparison of the lift and drag performances for the reference foil (Foil
276 “0000”) and its counterpart (Foil “1111”) with a full set of leading-edge tubercles, at a 4m/s
277 inflow velocity which corresponds to the highest Reynolds number that was achieved. Figure
278 18 clearly shows the beneficial effect of the tubercles on the lift coefficient and hence on the
279 lift-to-drag ratios. It is interesting to note in Figure 18 that the lift coefficients of both foils are
280 almost identical up to an angle of attack (AOA) of 9-10° after which Foil “1111” can maintain
281 a linear growth until 16° AOA while Foil “0000” cannot. This results in a 32% increase of the
282 lift-to-drag ratio for the foil with leading-edge tubercles compared to the reference foil, as
283 shown in Figure 19. Meanwhile the peak lift-to-drag ratio of Foil “1111” also shows a 5.8%
284 higher value at 4° AOA. From Figure 19, it is clear that the enhancement caused by the leading-
285 edge tubercles can be observed over the majority of the range of AOAs tested.

286 3.3.3 Performance Tests with Different Tubercle Coverage Arrangements

287 Although the beneficial effect of leading-edge tubercles covering the whole span of the foil has
288 been confirmed in the previous section, it has been reported in other research that this effect
289 may vary depending on the position and extent of the tubercles’ coverage relative to the foil
290 span [18]. Therefore 3 different tubercle coverage arrangements, which were described in
291 Section 3.1 as Foil “0001”, “0011”, “0111”, were tested to identify the optimum arrangement.
292 Five sets of tests, which also included the reference foil (“0000”) and the foil with full coverage
293 of tubercles (“1111”), were conducted at 3m/s and the results were compared, as shown in
294 Figure 20 to Figure 22. From the plots of the lift coefficients, it can be seen that the peak lift
295 coefficient tends to increase with the extent of the tubercles. As shown in Figure 20, Foil
296 “1111”, demonstrates the highest lift with a value of 1.48 at 16° AOA. Nevertheless this
297 arrangement also displays the highest drag. Based on the comparisons of the lift-to-drag ratios
298 of the tested arrangements, it appears that Foil “0001”, which had 1/4 of its leading-edge
299 covered with tubercles, displayed an overall better performance. This can be clearly seen in
300 Figure 21 and Figure 22 where Foil “0001” shows a positive impact from 0° to 26° AOA with
301 more than 10% enhancement in the maximum lift-to-drag ratio at 5° AOA, compared to the
302 reference (Foil “0000”). Even though Foil “1111” displayed the highest growth rate at 16° AOA,
303 Foil “0001” may offer more potential in improving the performance of a tidal turbine operating
304 over a wider range of tip speed ratios.

305 3.4 Flow Visualization Results and Analysis

306 3.4.1 Mapping the Flow Separation Region

307 Flow visualization tests with Foil “0000” and Foil “1111” were performed at a 3 m/s tunnel
308 inflow speed and at AOAs of 16° and 24°. For these conditions, the flow fields across three
309 selected sections along the foil span were visualised using the PIV device. The locations of the
310 selected sections are shown in Figure 23 for Foil “1111” and these positions were repeated for
311 Foil “0000”. For each test condition, 100 pairs of PIV images were analysed and averaged to
312 achieve the time-averaged data. The images of the flow fields and associated velocity vectors
313 at the three selected sections are shown in Table 3 and Table 4 for the AOA of 16° and 24°,
314 respectively.

315 Firstly, concentrating on the 16° AOA results in Table 3, as shown in the first column (Section1)
 316 the flow separation observed at the back of Foil “1111” is much stronger than the separation
 317 observed at the back of Foil “0000”. As the visualisation sections are getting closer to the foil
 318 tip the flow separation gradually vanishes as shown in the flow field results for “Section2” and
 319 “Section3”. This can be related to the strong rolling up effect of the tip vortex forming from
 320 the pressure side to the suction side of the foil which would reduce the flow separation. In fact,
 321 hardly any flow separation could be observed from the results of “Section2” and “Section3”
 322 with Foil “0000”.

323 On the other hand, as shown in Table 4, the results of the flow visualisations at 24° AOA
 324 indicate severe flow separation for both foils. However the separation experienced by Foil
 325 “1111” was even more severe than that experienced by Foil “0000”.

326 3.4.2 Development of Tip Vortex Cavitation

327 Perhaps the most striking difference between the flow pattern around Foil “0000” and Foil
 328 “1111”, was the development of a very strong tip vortex cavitation generated by Foil “0000”
 329 as opposed to almost no such cavitation generated by Foil “1111” due to the effect of the
 330 leading-edge tubercles. This can be clearly seen in the results given in Table 3 for the test
 331 condition with a 3m/s incoming velocity and 16° AOA. A close-up of this cavitating vortex,
 332 which emanated from the tip of the reference foil with about a 10mm diameter, is shown in
 333 Figure 24.

334 Using a typical cavitating Rankine vortex expression, the relationship between the diameter of
 335 the cavitating tip vortex, a_c , and its circulation, Γ , can be given by Equation 3 [25].

$$p_\infty - p_v = \frac{0.5\rho\Gamma^2}{4\pi^2 a_c^2} \quad \text{Equation (3)}$$

336 where, p_∞ is the pressure in far field and p_v is the saturated vapour pressure of the water.

337 According to Equation 3, the larger the diameter is, the stronger the vorticity. Since both foils
 338 were tested under the same conditions, the larger tip vortex cavitation experienced by the
 339 reference foil would be responsible for the stronger “end effect” and hence greater loss of lift.
 340 whereas its counterpart (Foil “1111”) with the leading-edge tubercles would maintain the 2D
 341 flow by lowering the end effect and therefore experience more favourable lift characteristics
 342 for the same condition.

343 3.4.3 Concluding Remarks on the Effect of Leading-Edge Tubercles

344 Based on the observations and analyses so far, by combining our understandings from the flow
 345 analysis with regard to the effect of different grades of flow separation and that of tip cavitation
 346 generation with and without leading-edge tubercles, we can conclude that the leading-edge
 347 tubercles can effectively weaken the 3 dimensional effect of the hydrofoil.

348 This hypothesis has been firstly supported by the evidence of much weaker separations
 349 observed on the back of the reference foil with the smooth leading edge compared to the much
 350 more severe separations observed on the counterpart foil with the leading-edge tubercles. Since

351 the measuring sections are very close to the tip, the 3D effect generates the rolling up flow
352 which can reduce the flow separation close to the tip region. Therefore the more severe the
353 flow separation at the tip region is, the weaker the 3D effect is.

354 On the other hand the hypothesis was also complemented by the evidence of suppressed tip
355 vortex cavitation and hence much reduced vortex strength resulting from the leading-edge
356 tubercles. This also supported that the 3D effect was weakened by the leading-edge tubercles.

357 **4 Conclusions**

358 This paper reports research into the design, optimization and validation of a tidal turbine blade
359 to exploit the potential benefits of biomimetics in the form of leading-edge tubercles. Based on
360 the research so far, the following conclusions can be drawn:

361 1. As demonstrated in the optimisation study based on the 2D foil, while the application
362 of leading-edge tubercles could maintain high lift coefficients under post-stall
363 conditions, it could also lower the magnitude of the maximum lift. Based on the
364 optimisation study, a sinusoidal form of leading-edge tubercle profile with $0.1C$ height
365 and $0.5C$ wavelength appeared to be a good compromise for an optimum design and
366 this was applied on a 3D foil which was model tested to validate its performance.

367 2. Comparative model tests of the 3D foil with a smooth leading edge (no tubercles) and
368 with the leading tubercles, which covered the whole span of the foil, confirmed the
369 significant benefits of the tubercles on the lift and lift-to-drag ratio of the foil despite a
370 slight increase in the drag characteristics. A maximum improvement of 32% in C_L/C_D
371 can be gained in the post stall region at a 16° of angle of attack due to the linear increase
372 of the lift coefficient maintained with the increase of the angle of attack.

373 3. By optimising the application length of the leading-edge tubercles along the foil span,
374 it was found that the maximum lift coefficient was reduced with the reduced tubercle
375 application length. However, due to the enhanced lift coefficients before the stall and
376 compromised increase in the drag coefficient, the foil with the shortest tubercle
377 application length, which was equal to a $1/4$ of the span, at the tip region displayed the
378 best overall performance amongst the different combinations tested. This was based on
379 the increased lift-to-drag coefficient ratio over the wider range of angles of attack and
380 more than 10% increase in the peak lift-to-drag ratio.

381 4. The flow visualisations of the 3D foil with and without the leading-edge tubercles
382 indicated that the strong tip vortex caused by the well-known end effect can be reduced
383 dramatically by the application of the tubercles which maintain the 2 dimensional
384 characteristics of the flow around the 3D foil.

385 Based on this research, the biomimetic exploitation of tubercles on tidal turbine blades has been
386 shown to be promising. However further fundamental research investigating the tubercle
387 concept and a thorough investigation on tidal turbine models are necessary.

388 **Acknowledgments**

389 This research is funded by the School of Marine Science and Technology, Newcastle
390 University and China Scholarship Council. Hence the financial support obtained from both
391 establishments is gratefully acknowledged. The Authors would like to thank all the team
392 members in the Emerson Cavitation Tunnel for the help in testing and sharing their knowledge.

393 **Reference**

- 394 [1] F.E. Fish, P.W. Weber, M.M. Murray, L.E. Howle, The tubercles on humpback whales'
395 flippers: application of bio-inspired technology, *Integrative and comparative biology*, 51 (2011)
396 203-213.
- 397 [2] Frank E. Fish, J.M. Battle, Hydrodynamic design of the humpback whale flipper, *Journal of*
398 *Morphology*, (1996).
- 399 [3] K. L. Hansen, R. M. Kelso, B.B. Dally, The effect of leading edge tubercle geometry on the
400 performance of different airfoils, (2009).
- 401 [4] H.S. Yoon, P.A. Hung, J.H. Jung, M.C. Kim, Effect of the wavy leading edge on hydrodynamic
402 characteristics for flow around low aspect ratio wing, *Computers & Fluids*, 49 (2011) 276-289.
- 403 [5] H. Johari, C. Henoeh, D. Custodio, A. Levshin, Effects of leading-edge protuberances on
404 airfoil performance, *Aiaa J*, 45 (2007) 2634-2642.
- 405 [6] D.S. Miklosovic, M.M. Murray, L.E. Howle, Experimental evaluation of sinusoidal leading
406 edges, *J Aircraft*, 44 (2007) 1404-1408.
- 407 [7] M.J. Stanway, Hydrodynamic effects of leading-edge tubercles on control surfaces and in
408 flapping foil propulsion, in, *Massachusetts Institute of Technology*, 2008.
- 409 [8] P.W. Weber, L.E. Howle, M.M. Murray, Lift, drag, and cavitation onset on rudders with
410 leading-edge tubercles, *Mar Technol Sname N*, 47 (2010) 27-36.
- 411 [9] A. Corsini, G. Delibra, A.G. Sheard, On the role of leading-edge bumps in the control of stall
412 onset in axial fan blades, *J Fluid Eng-T Asme*, 135 (2013) 081104-081104.
- 413 [10] T. Swanson, K.M. Isaac, Biologically Inspired Wing Leading Edge for Enhanced Wind
414 Turbine and Aircraft Performance, in, *AIAA*, 2011.
- 415 [11] E. van Nierop, S. Alben, M. Brenner, How bumps on whale flippers delay stall: An
416 aerodynamic model, *Physical Review Letters*, 100 (2008).
- 417 [12] L. Bellequant, L.E. Howle, Whalepower wenvor blade, (2009).
- 418 [13] K.L. Hansen, R.M. Kelso, B.B. Dally, Performance variations of leading-edge tubercles for
419 distinct airfoil profiles, *Aiaa J*, 49 (2011) 185-194.

- 420 [14] D.C.a.L.M. Mark W. Lohry, Characterization and Design of Tubercle Leading-Edge Wings,
421 in: Seventh International Conference on Computational Fluid Dynamics (ICCFD7), Big Island,
422 Hawaii, 2012.
- 423 [15] J.H. Chen, S.S. Li, V.T. Nguyen, The effect of leading edge protuberances on the
424 performance of small aspect ratio foils.
- 425 [16] G. Sisinni, D. Pietrogiaconi, G.P. Romano, Biomimetic wings, *Advances in Science and*
426 *Technology*, 84 (2012) 72-77.
- 427 [17] D.S. Miklosovic, M.M. Murray, L.E. Howle, F.E. Fish, Leading-edge tubercles delay stall on
428 humpback whale (*Megaptera novaeangliae*) flippers, *Phys Fluids*, 16 (2004) L39-L42.
- 429 [18] T. Gruber, M.M. Murray, D.W. Fredriksson, Effect of humpback whale inspired tubercles
430 on marine tidal turbine blades, in: ASME 2011 International Mechanical Engineering Congress
431 and Exposition, American Society of Mechanical Engineers, 2011, pp. 851-857.
- 432 [19] D. Wang, M. Atlar, R. Sampson, An experimental investigation on cavitation, noise, and
433 slipstream characteristics of ocean stream turbines, *Proceedings of the Institution of*
434 *Mechanical Engineers, Part A: Journal of Power and Energy*, 221 (2007) 219-231.
- 435 [20] D.M. Somers, Design and experimental results for the S814 airfoil, in, National Renewable
436 Energy Laboratory, NREL/SR-440-6919 • UC Category: 1213 • DE97000104, 1997.
- 437 [21] J. Janiszewska, R.R. Ramsay, M. Hoffmann, G. Gregorek, Effects of grit roughness and
438 pitch oscillations on the S814 airfoil, in, National Renewable Energy Lab., Golden, CO (United
439 States), 1996.
- 440 [22] F. Menter, M. Kuntz, R. Langtry, Ten years of industrial experience with the SST
441 turbulence model, *Turbulence, heat and mass transfer*, 4 (2003) 625-632.
- 442 [23] ANSYS, Release 14.5 Documentation, Inc ANSYS, (2013).
- 443 [24] M. Atlar, Recent upgrading of marine testing facilities at Newcastle University, in:
444 AMT'11, the second international conference on advanced model measurement technology
445 for the EU maritime industry, 2011, pp. 4-6.
- 446 [25] J.B.W. McCormick, On Cavitation Produced by a Vortex Trailing From a Lifting Surface,
447 *Journal of Fluids Engineering*, 84 (1962) 369-378.

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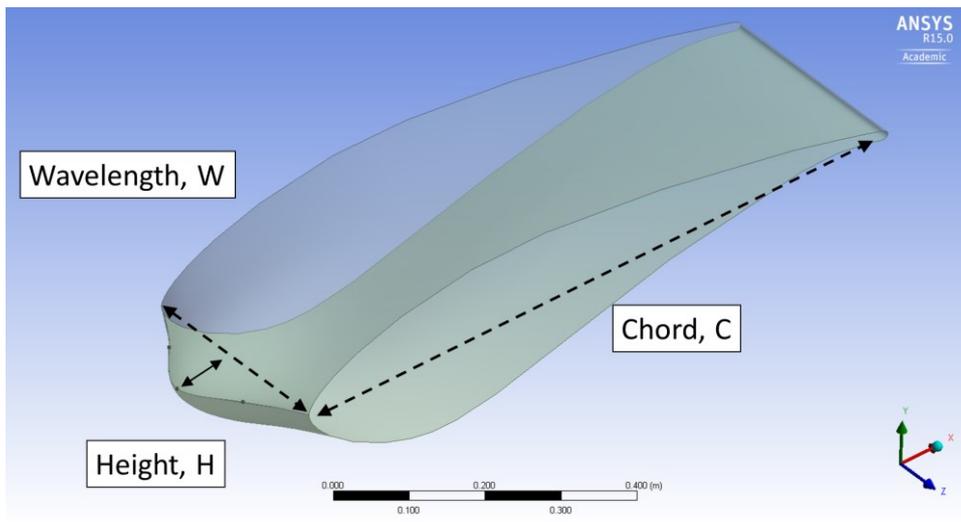
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Figure 1 Cross-section profile of S814 [19]



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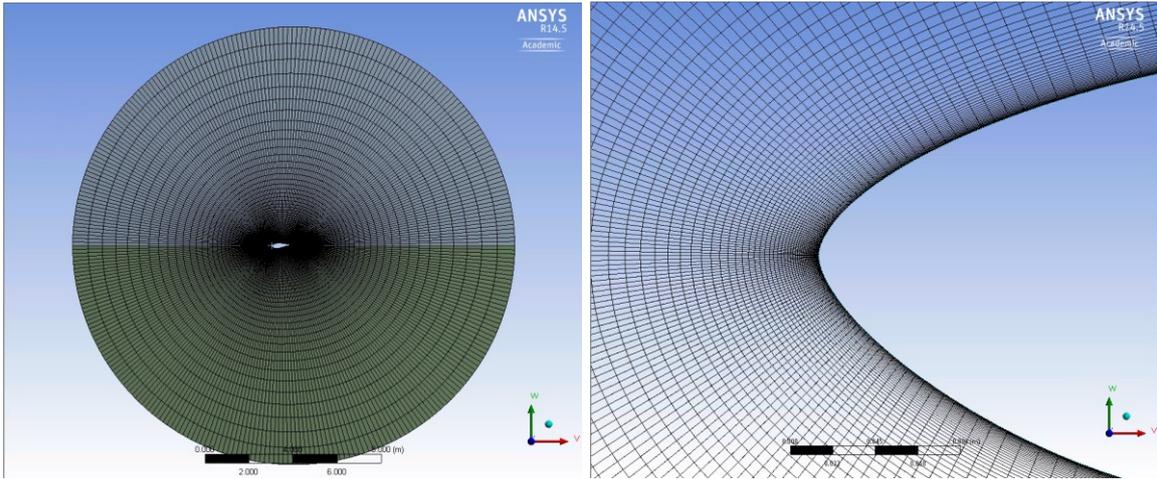
Figure 2 Scaled tidal turbine model mounted on the dynamometer of Emerson Cavitation Tunnel [19]



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Figure 3 Definition of 2D foil with a sinusoidal tubercle

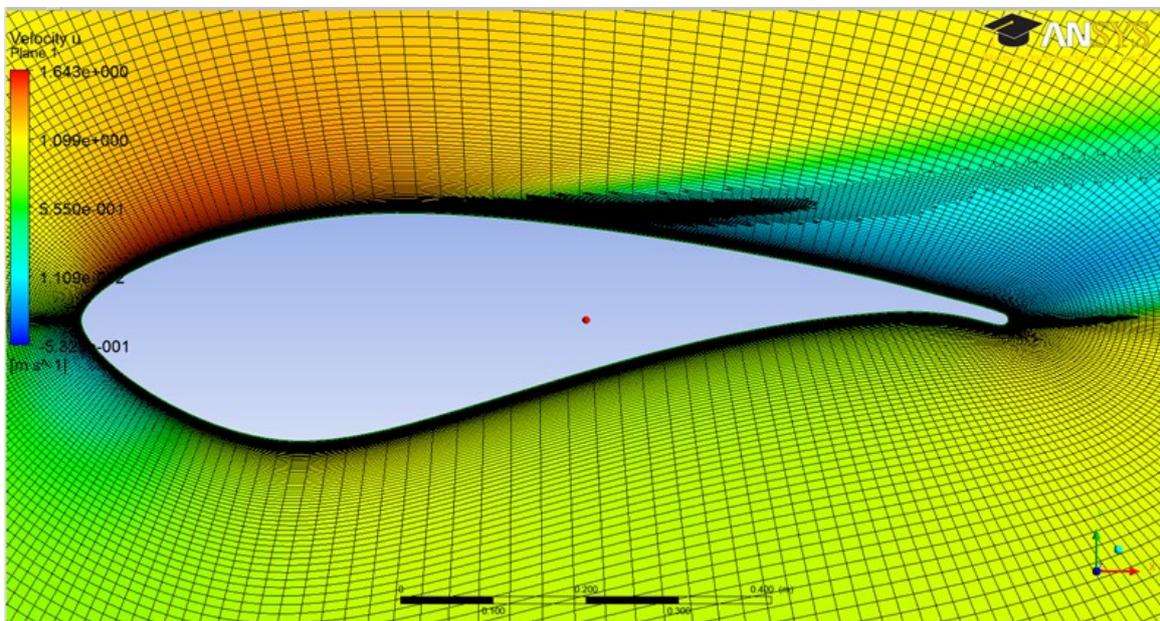
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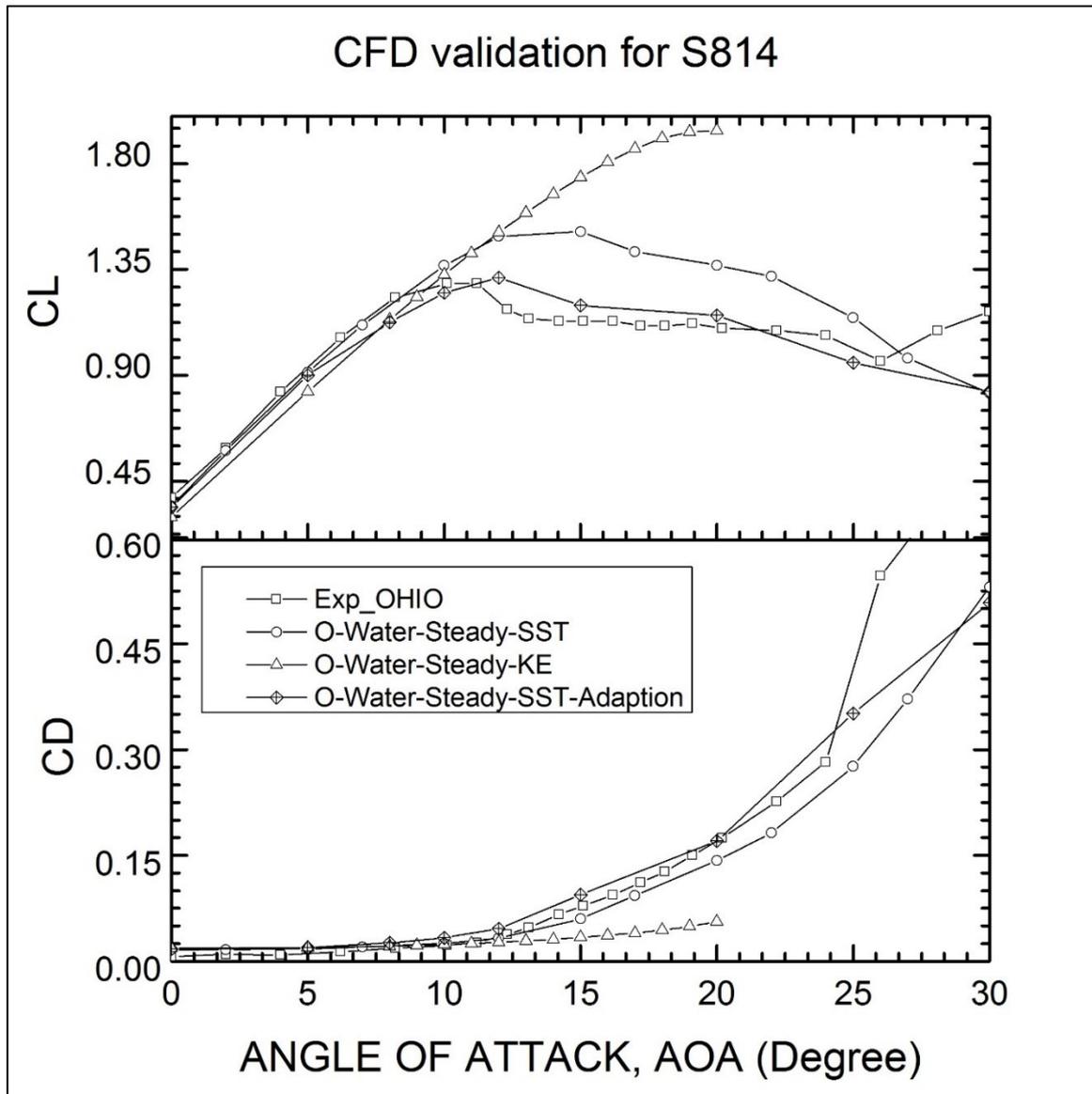
Figure 4 Mesh overview (left) and zoom-in view of wing section at the leading edge (right)

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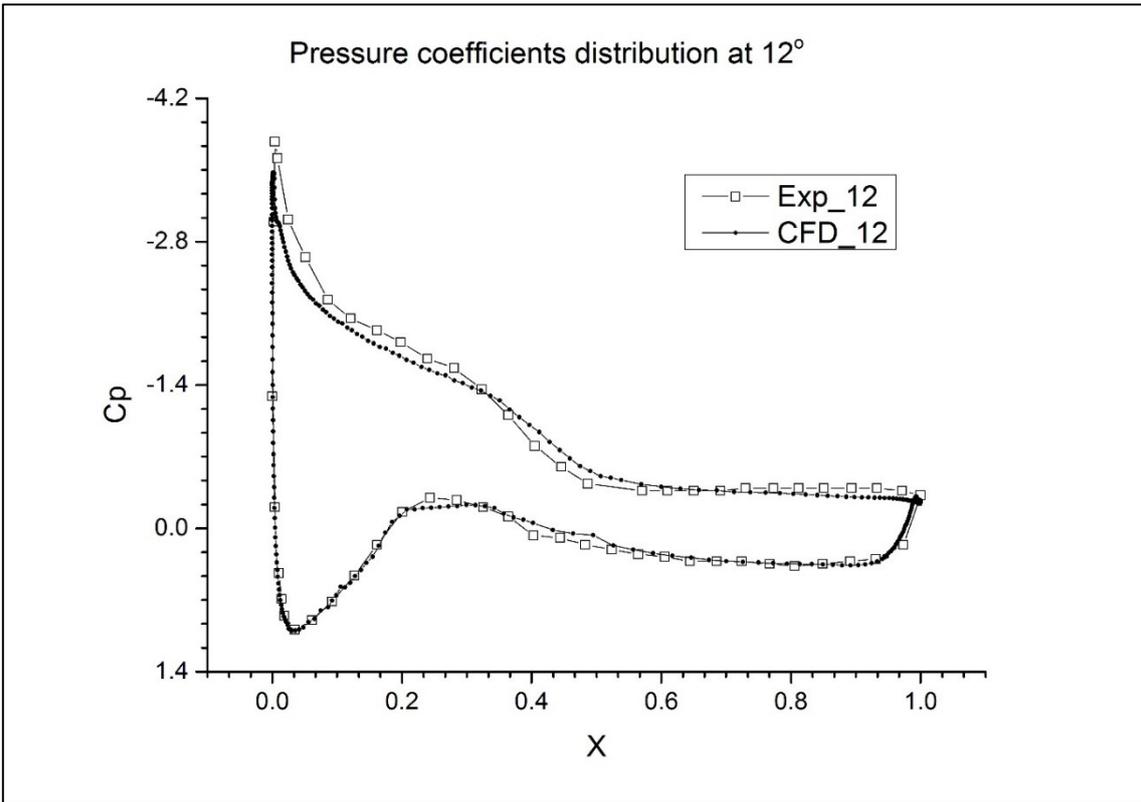
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Figure 5 Refined mesh by the "solution adaptive mesh" method



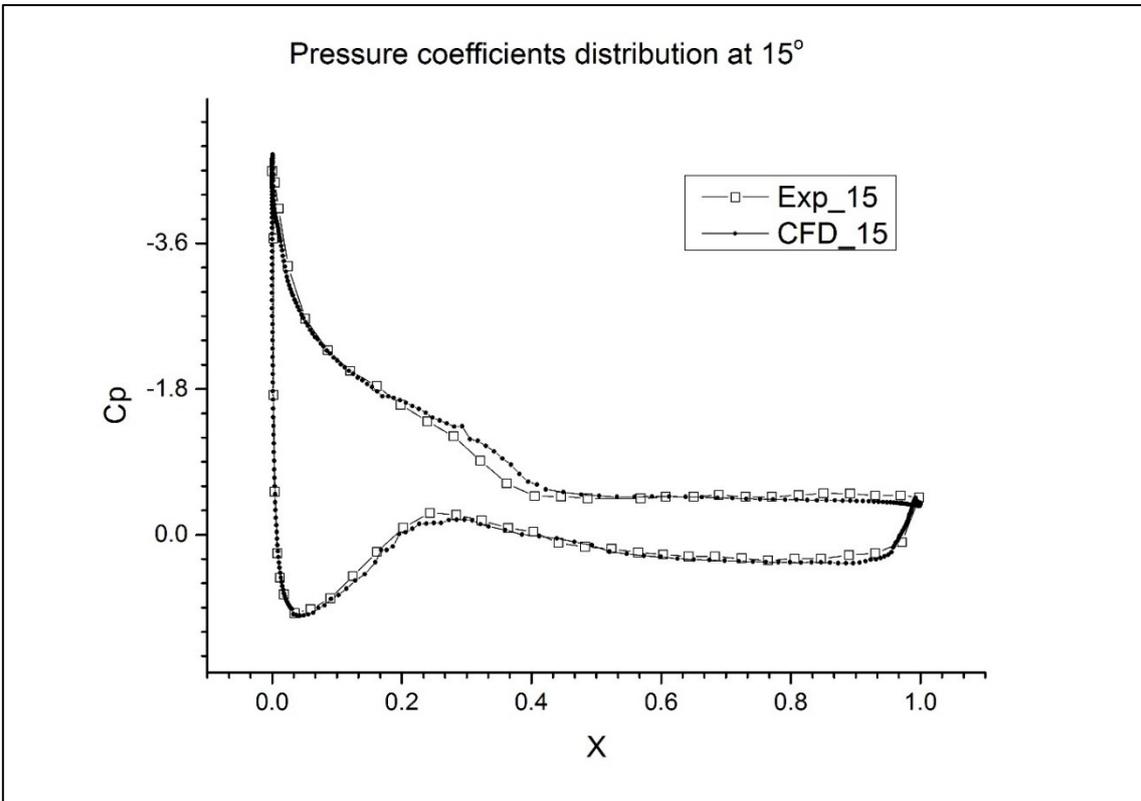
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Figure 6 Validation for CFD prediction of lift and drag coefficients of S814 airfoil



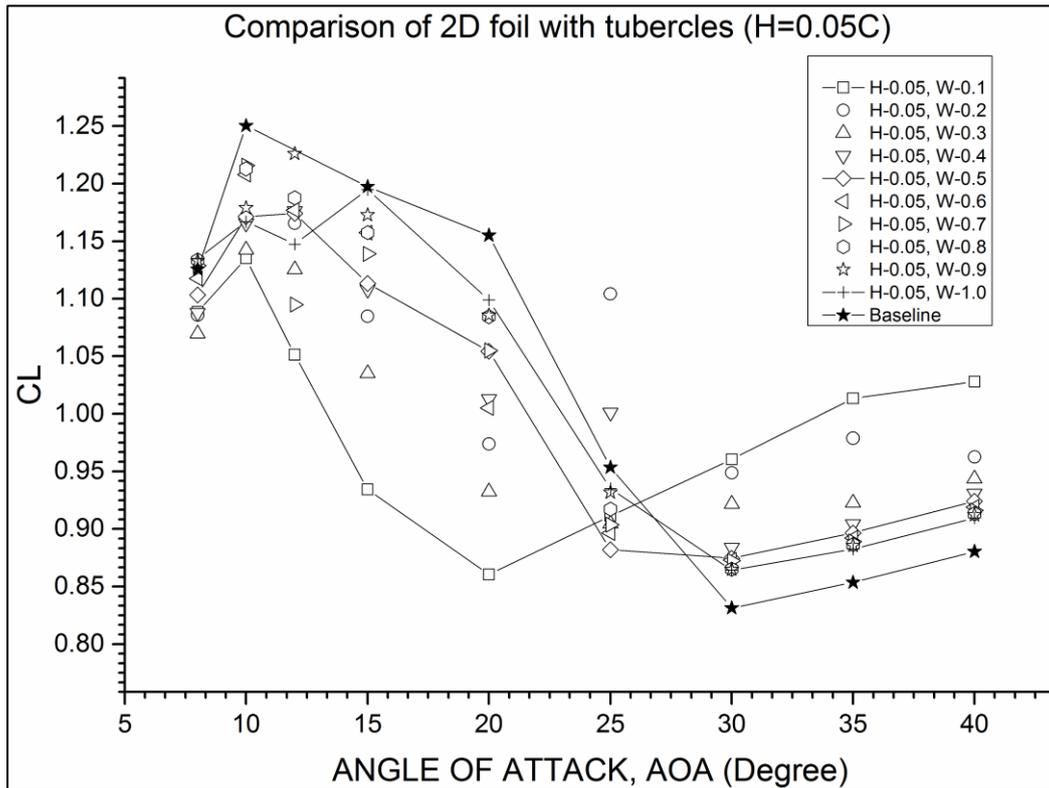
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Figure 7 Validation for CFD prediction of Pressure coefficient distribution at 12° of angle of attack



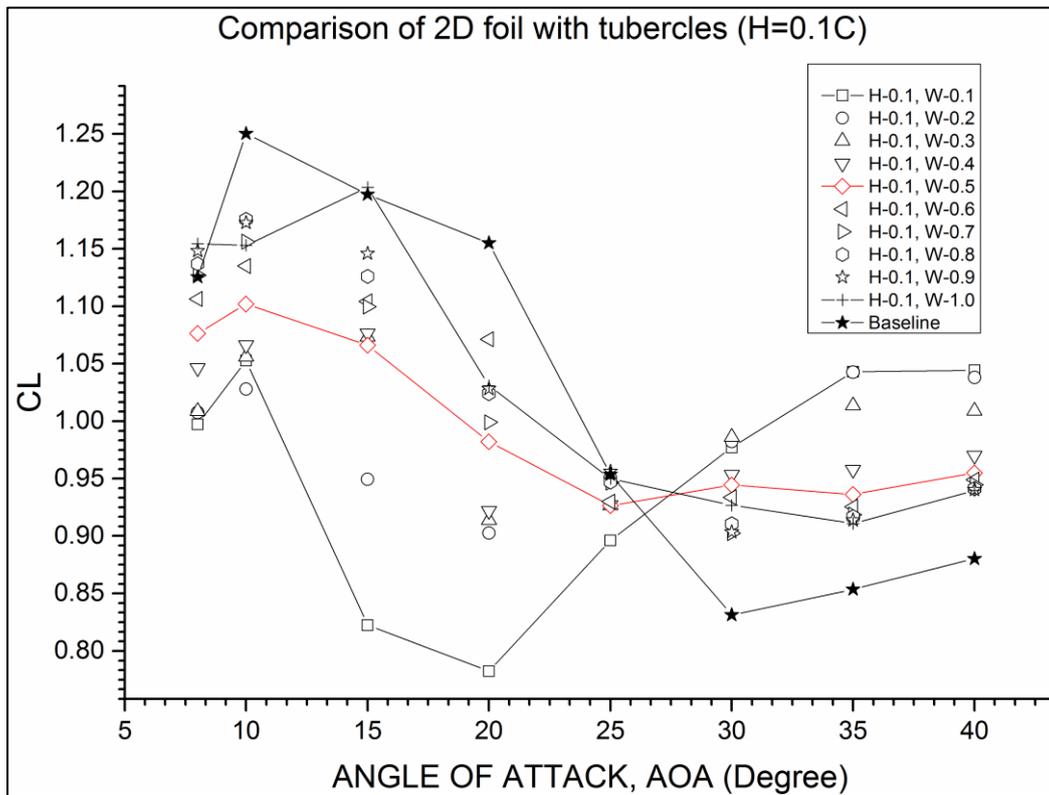
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Figure 8 Validation for CFD prediction of Pressure coefficient distribution at 15° of angle of attack



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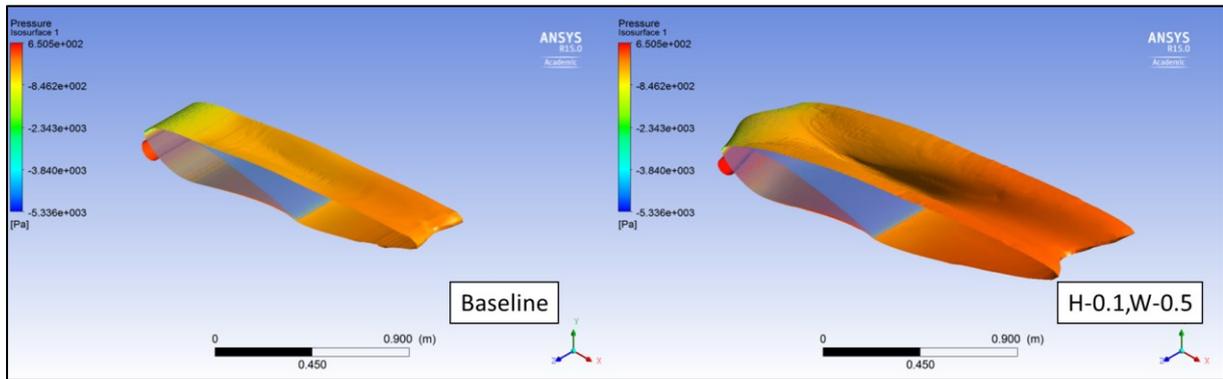
Figure 9 Comparison of 2D foil lift coefficients with different tubercle profiles by varying the wavelength (W) at constant tubercle height (H=0.05C)



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Figure 10 Comparison of 2D foil lift coefficients with different tubercle profiles by varying the wavelength (W) at constant tubercle height (H=0.1C)

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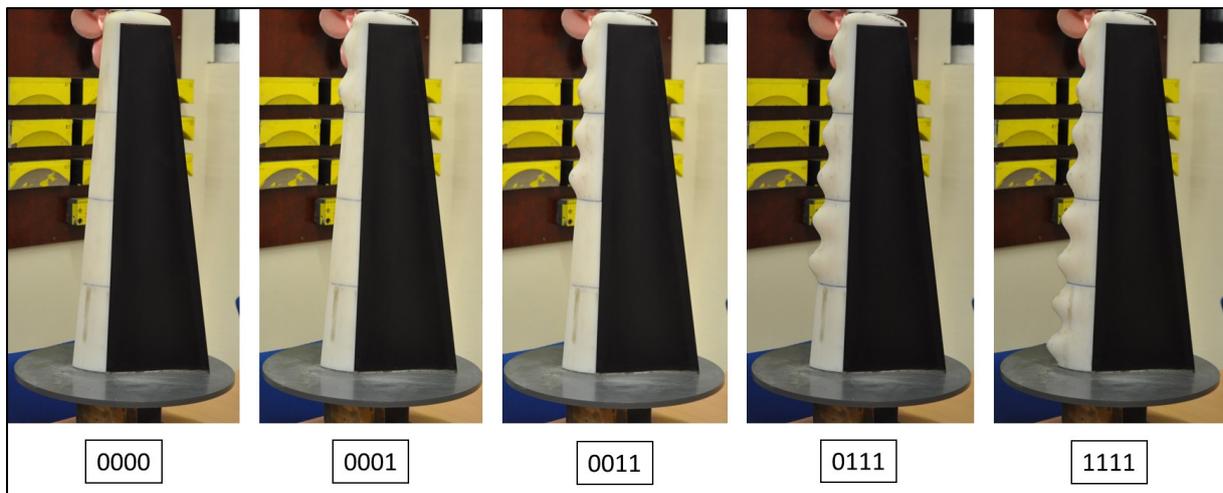


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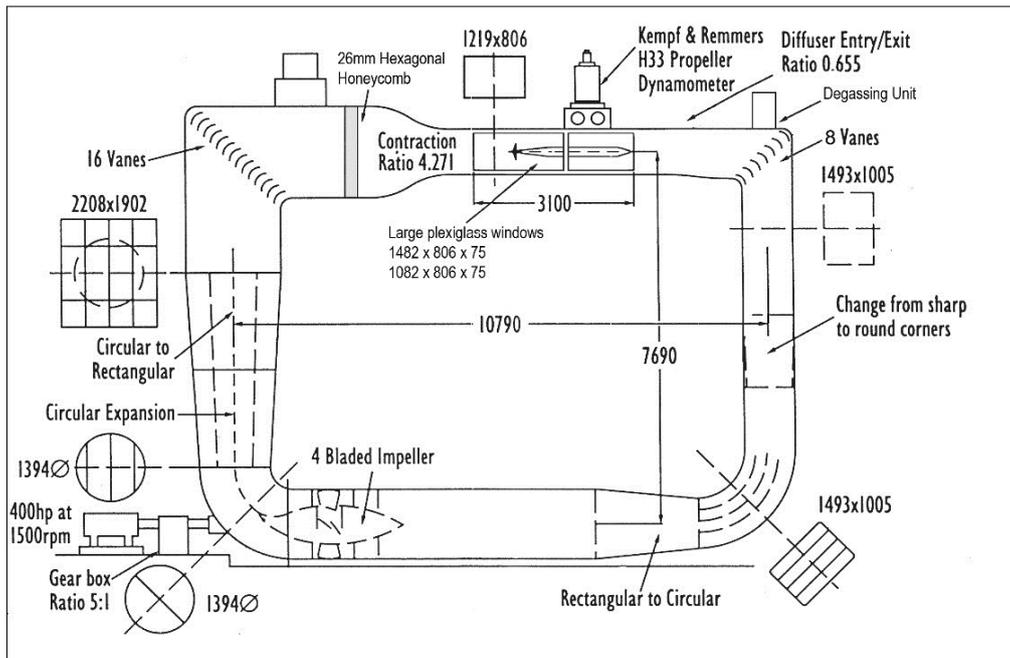
Figure 11 Comparison of flow separation at 15° angle of attack (Velocity isosurface at 50% of incoming velocity coloured by pressure distribution)



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Figure 12 Tested 3D hydrofoil models with interchangeable leading-edge parts



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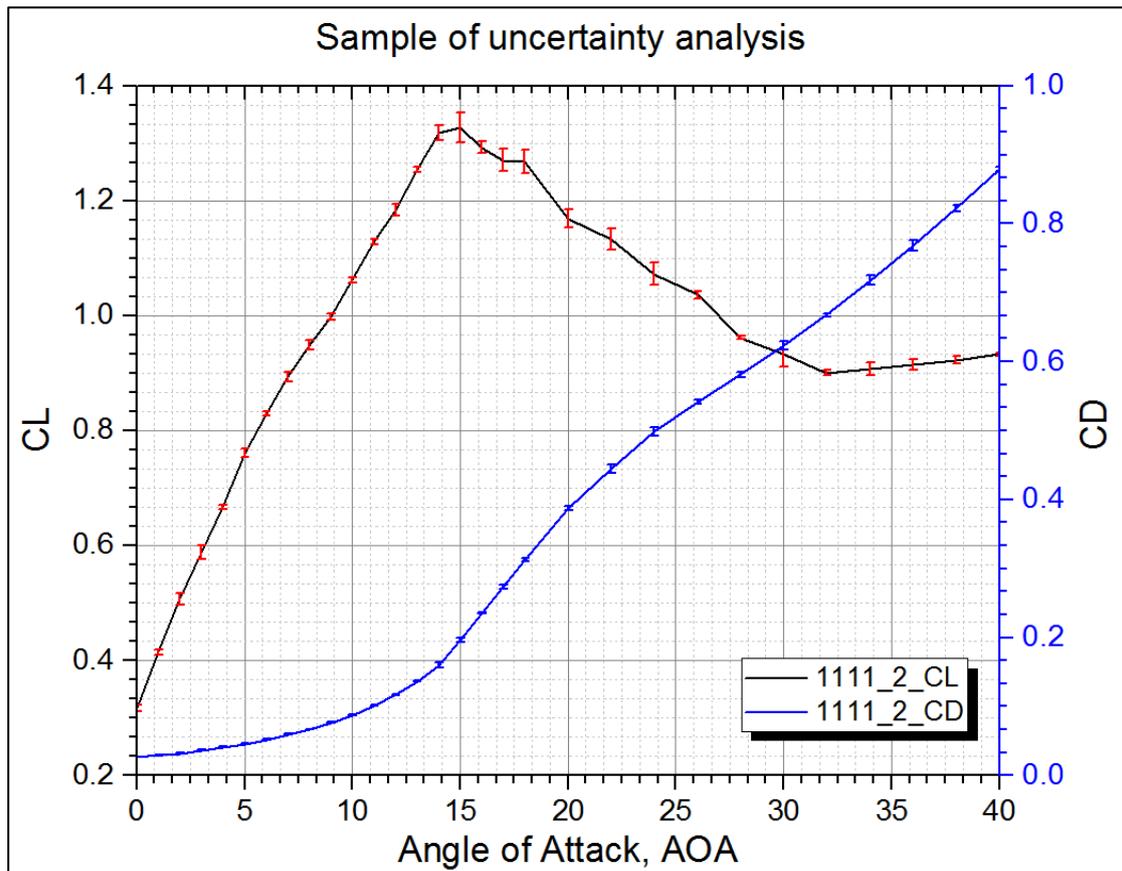
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Figure 13 Sketch of the Emerson Cavitation Tunnel



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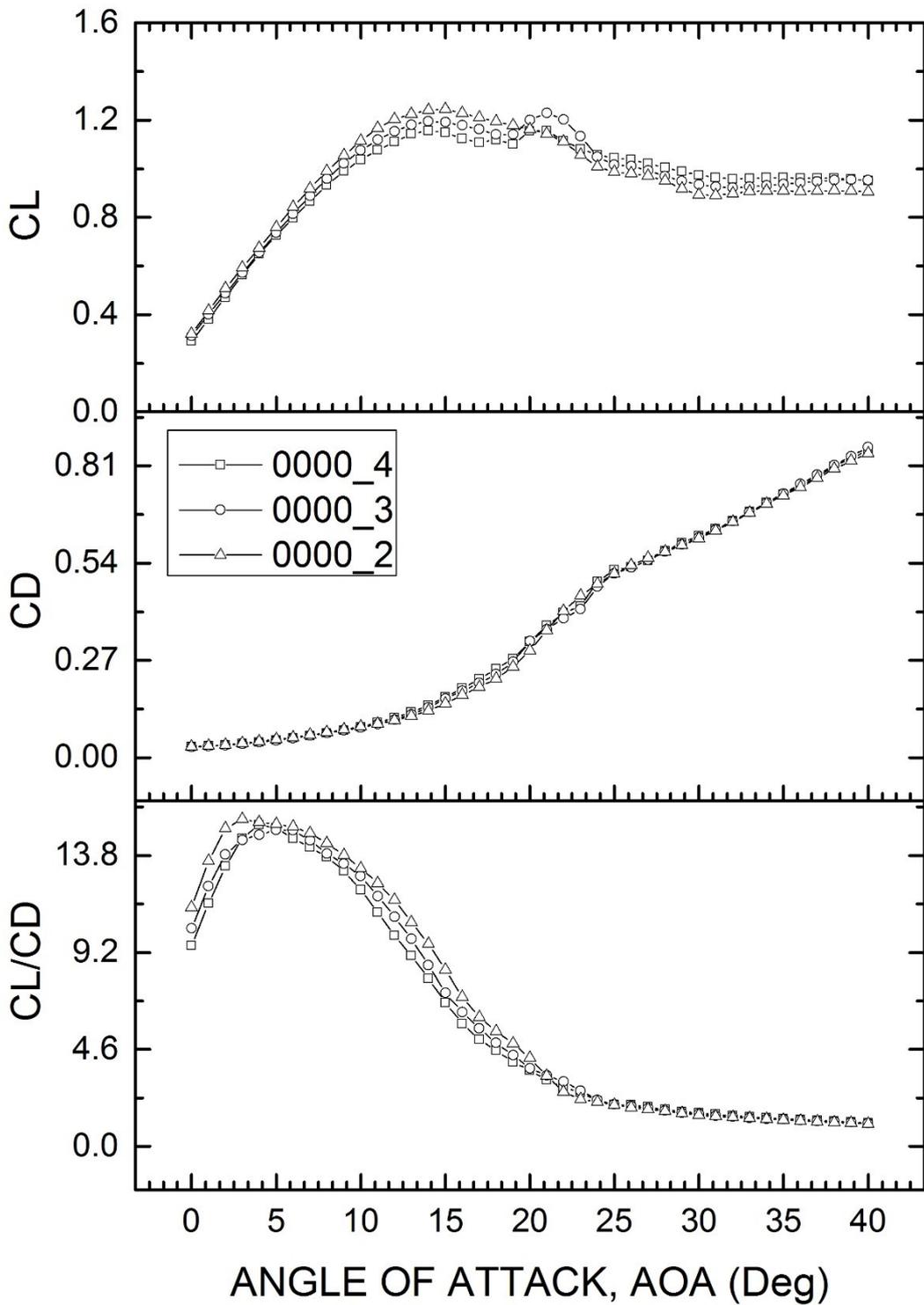
Figure 14 Setup of 3-component balance (Cussons R102) on the Emerson Cavitation Tunnel upper lid (Left) and setup of tested foil mounted on the 3-component balance (right)



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Figure 15 Sample of uncertainty analysis results applied on the measured lift and drag coefficients

Reynolds number effect on "0000"



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Figure 16 Experimental data for Foil "0000" with smooth leading edge at different incoming velocities

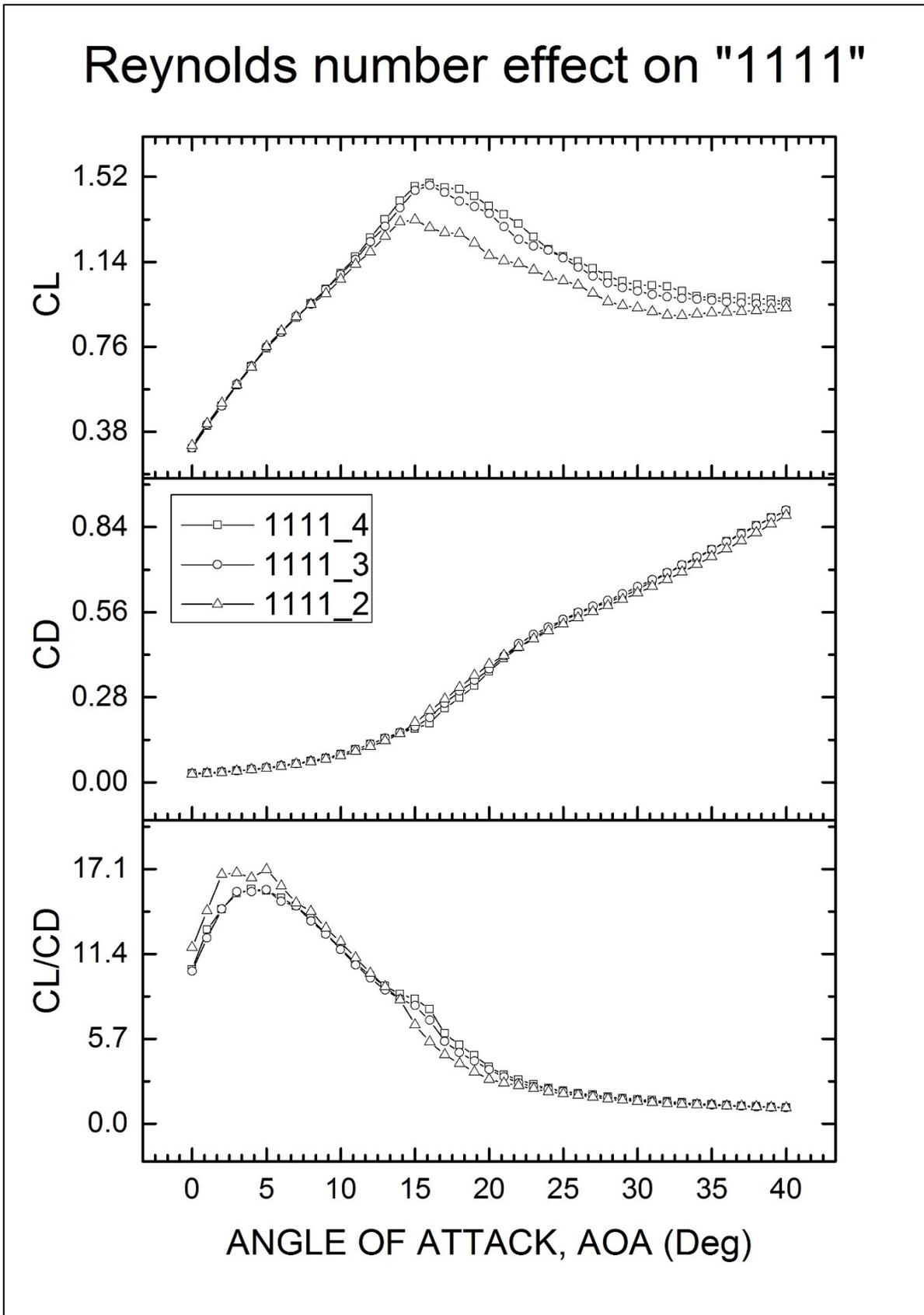
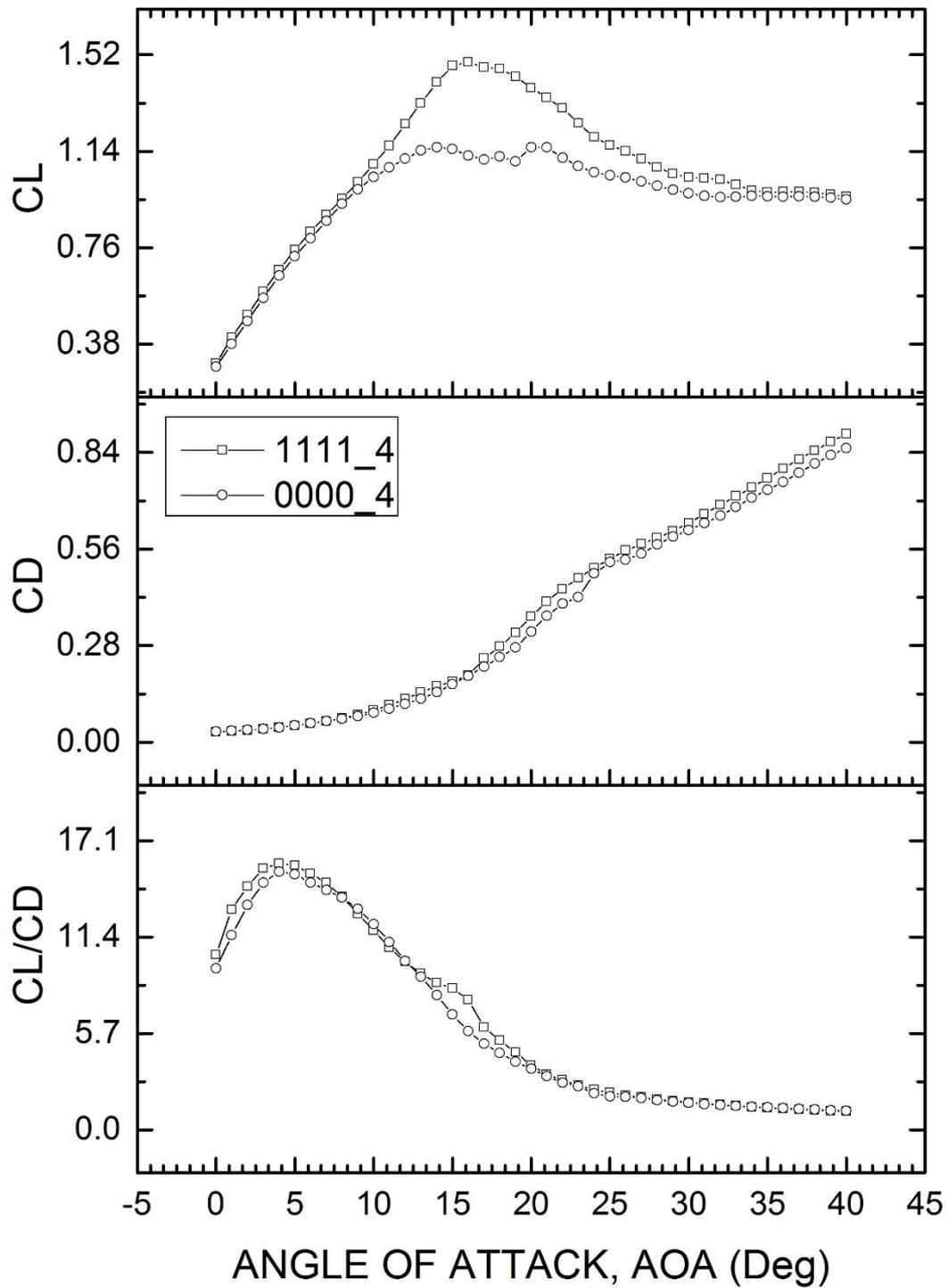


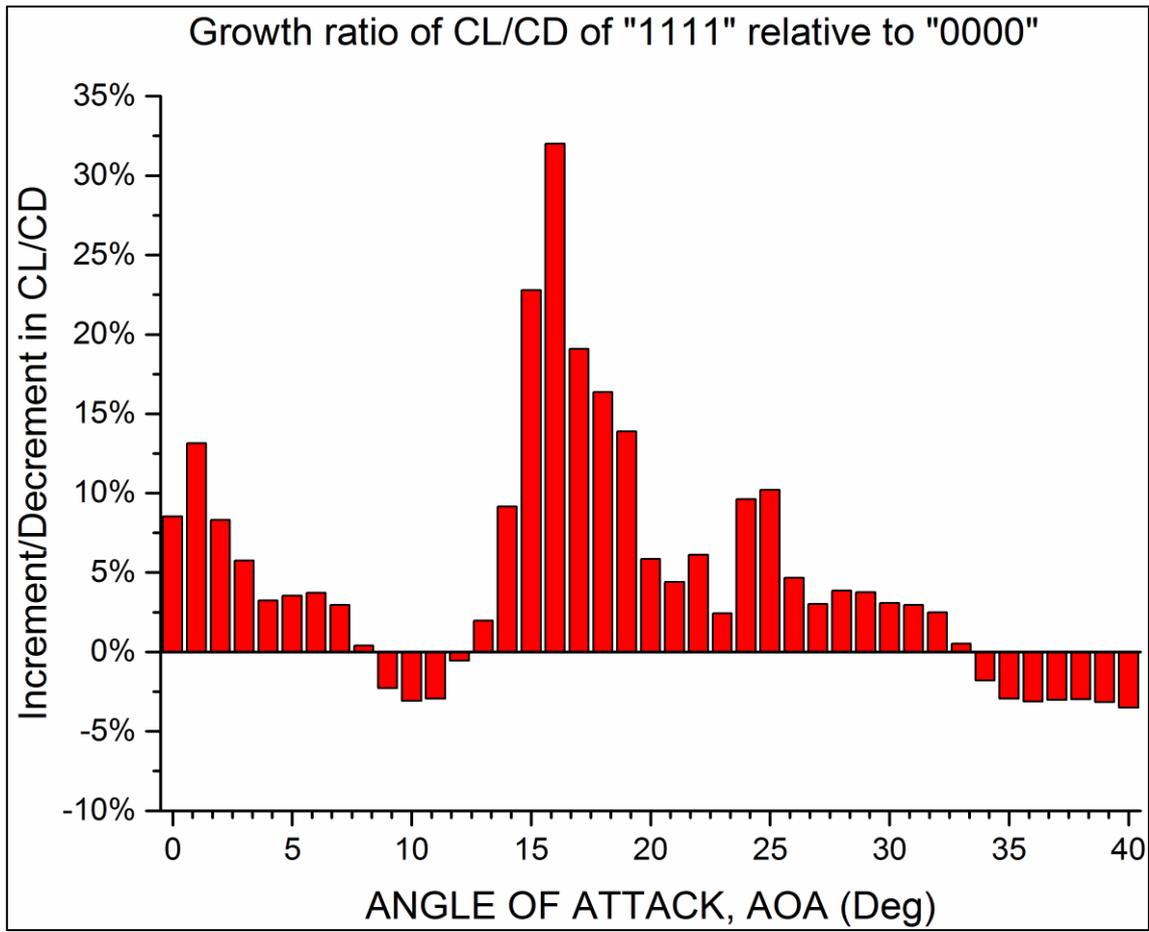
Figure 17 Experimental data for Foil "1111" with leading-edge tubercles at different incoming velocity

Comparison between "1111" and "0000"



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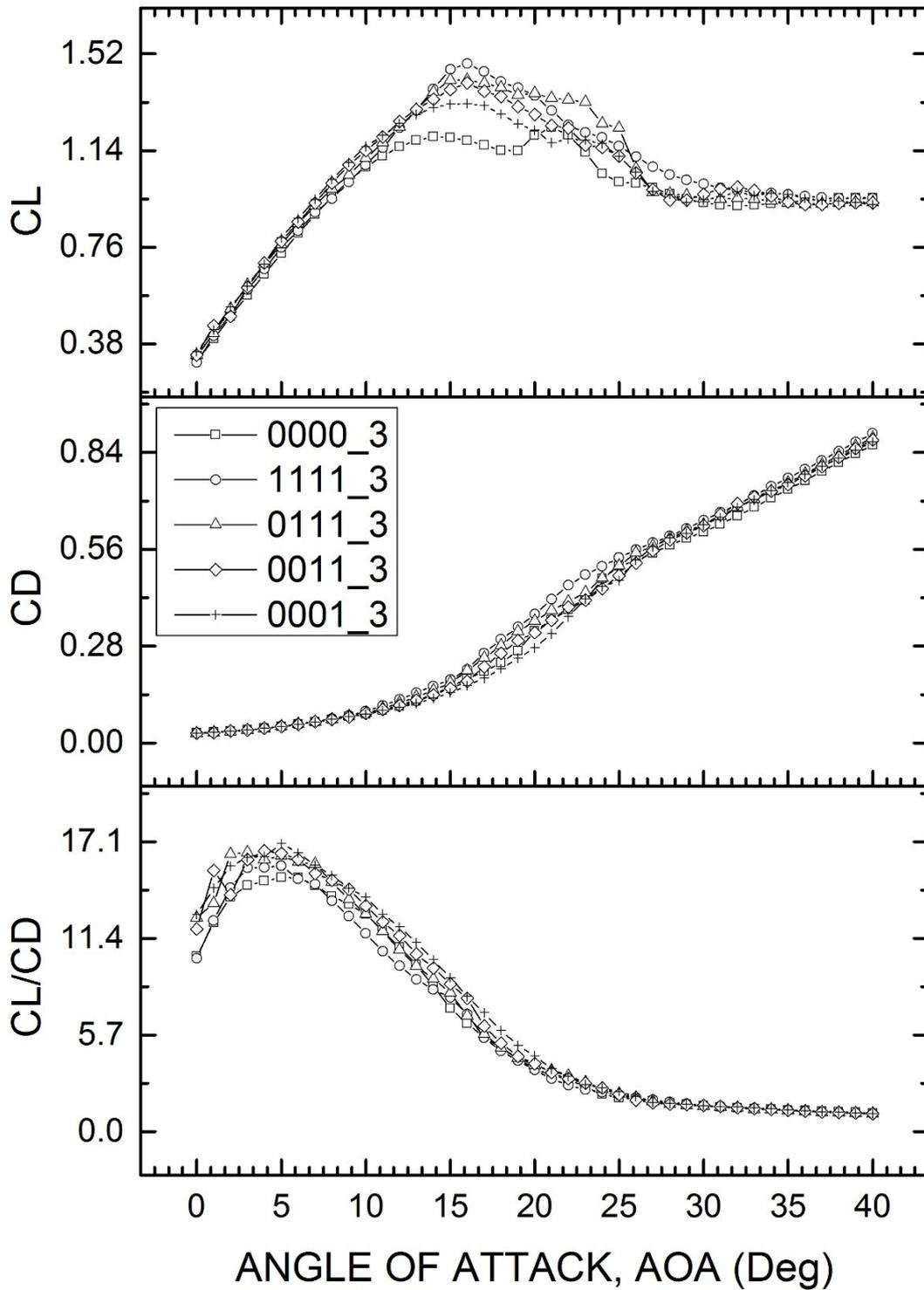
Figure 18 Comparison of experimental data for Foil "0000" and Foil "1111" at 4m/s



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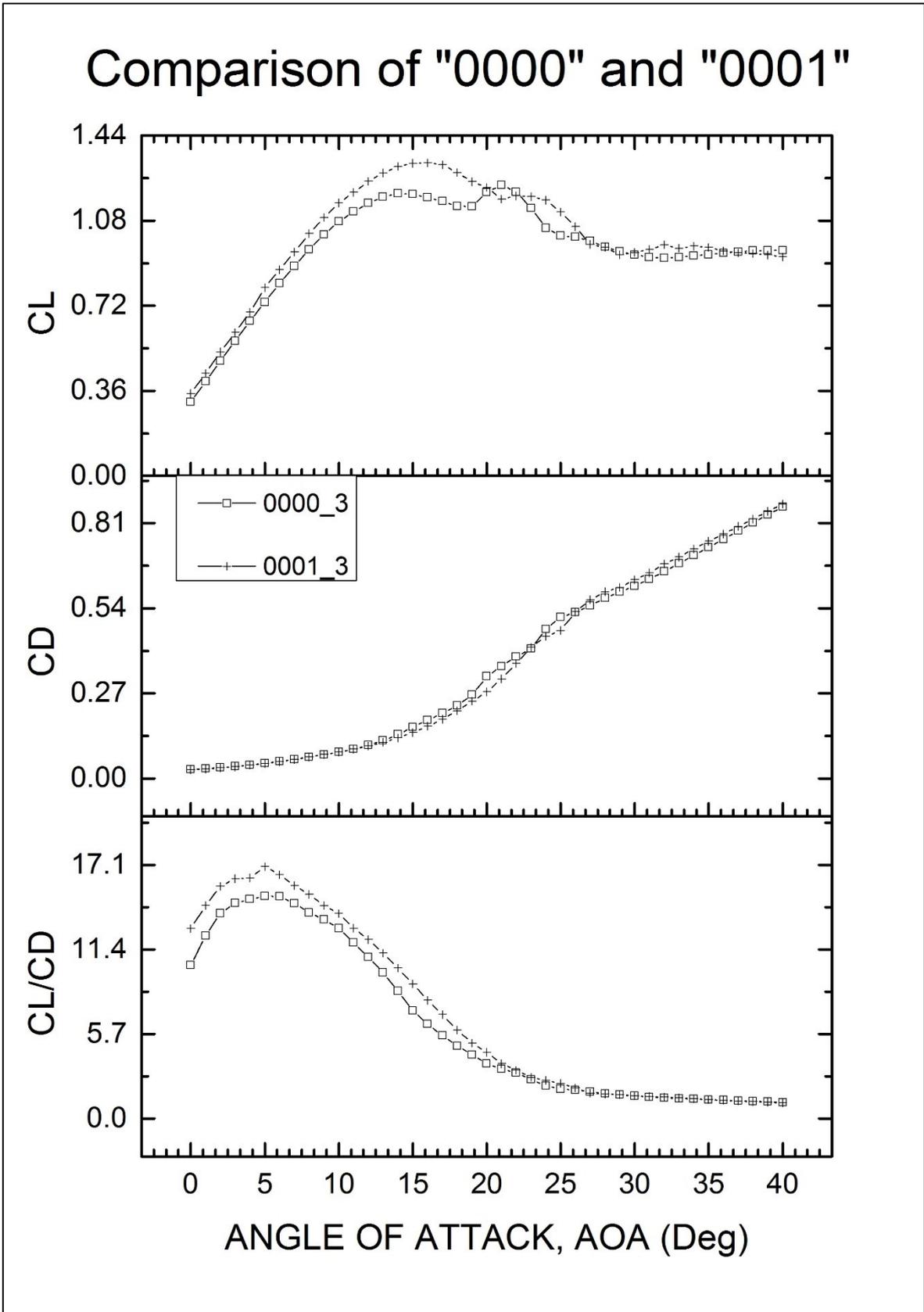
Figure 19 Growth ratio of C_L/C_D for Foil "1111" (with leading-edge tubercles) relative to Foil "0000" (with smooth leading edge)

Comparison of different configurations



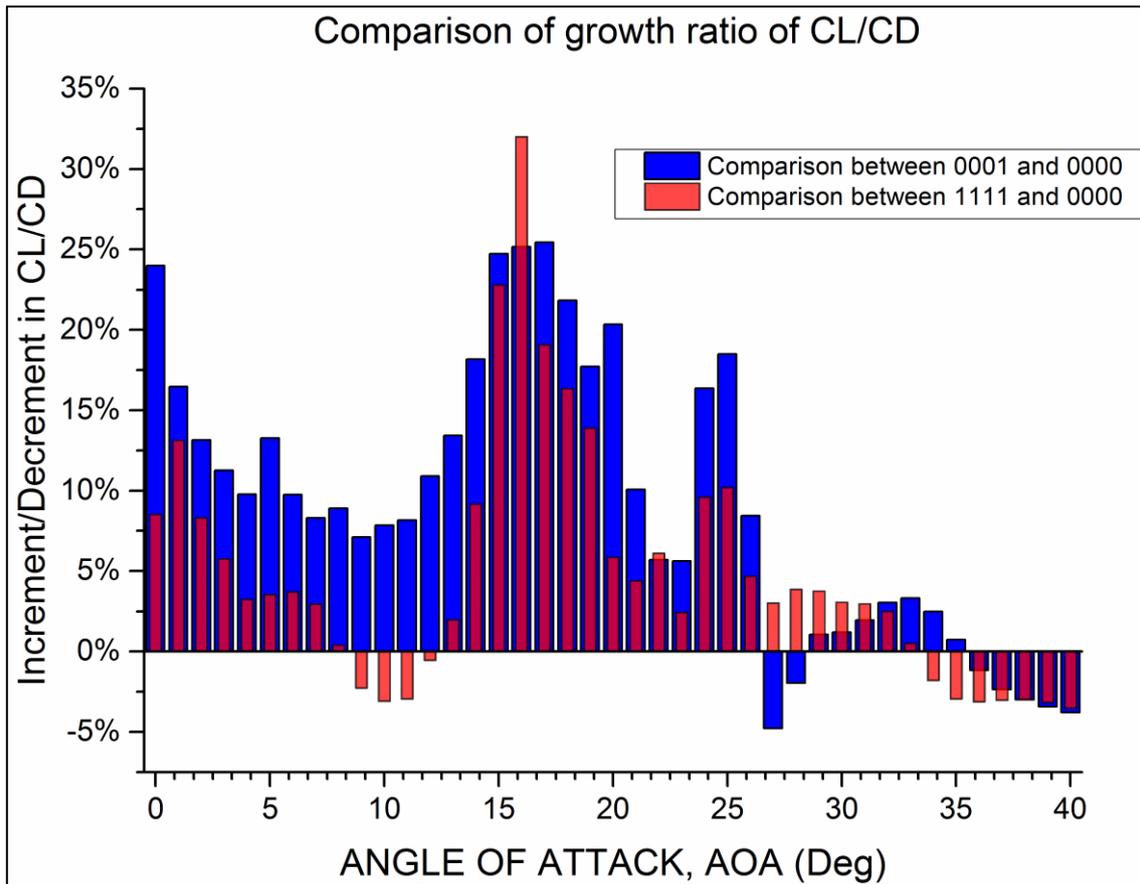
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Figure 20 Comparison of experimental data for different leading-edge tubercle coverage arrangements



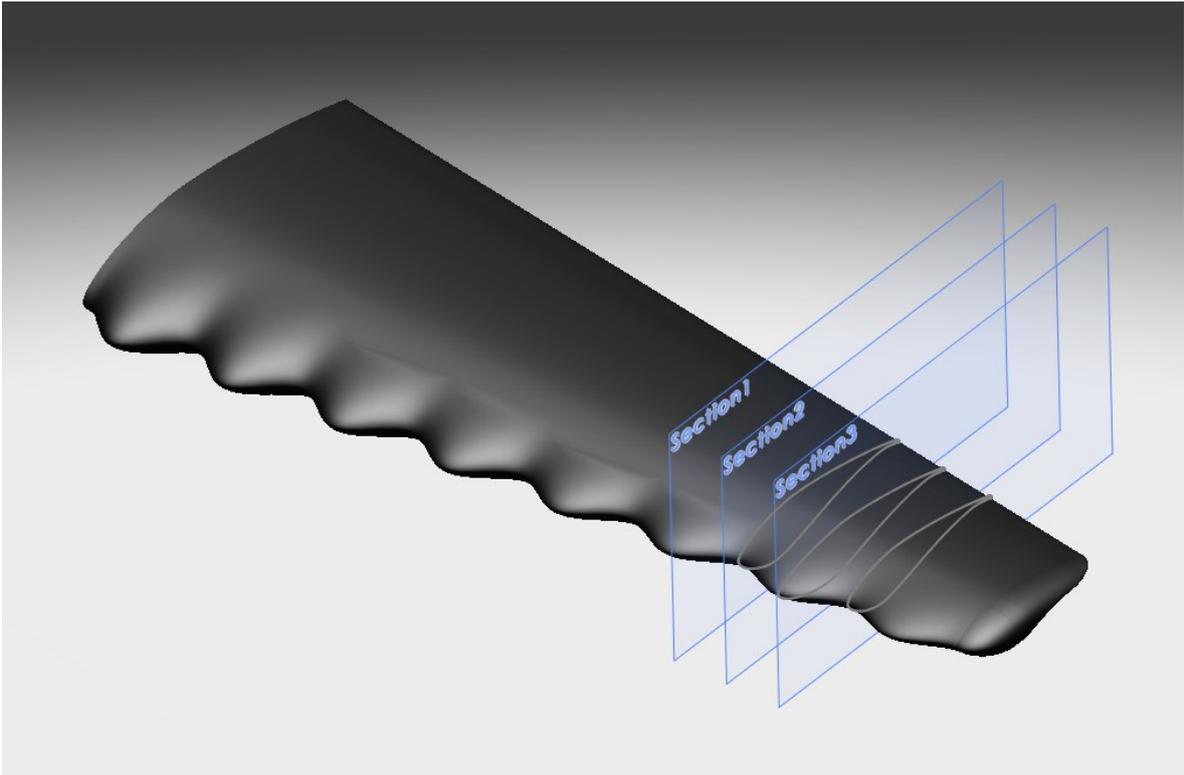
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Figure 21 Comparison of experimental data for foil with minimum leading-edge tubercle coverage ("0001") and for the reference foil ("0000") at 3m/s.



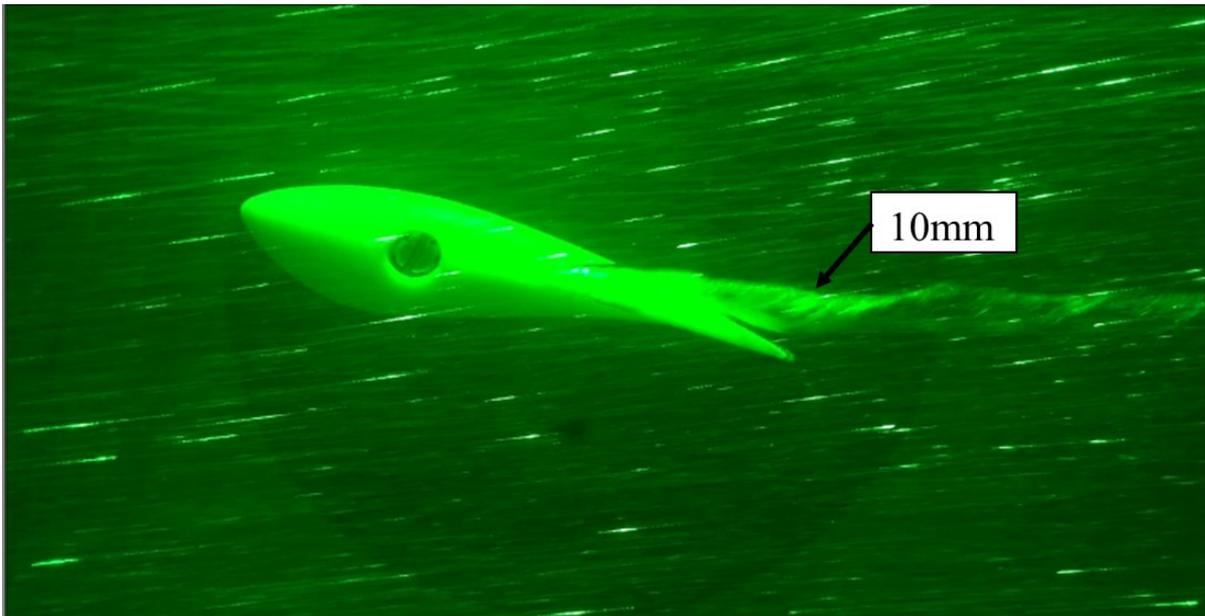
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Figure 22 Comparison of relative growth ratios for C_L/C_D for Foil “1111” (with leading-edge tubercles applied on whole span) and Foil “0001” (with minimum leading-edge tubercles applied around the tip)



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Figure 23 Sectional positions selected along Foil “1111” for flow visualization using PIV



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Figure 24 Cavitating tip vortex observation on reference foil with smooth leading edge
(Note a 10mm diameter tip vortex cavitation was generated)

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Table 1 Chord distribution of the reference foil

Span(mm)	0	70	140	210	280	350	420	490	560
Chord(mm)	225.1	210.08	195.06	180.04	165.02	150	134.98	119.96	104.94

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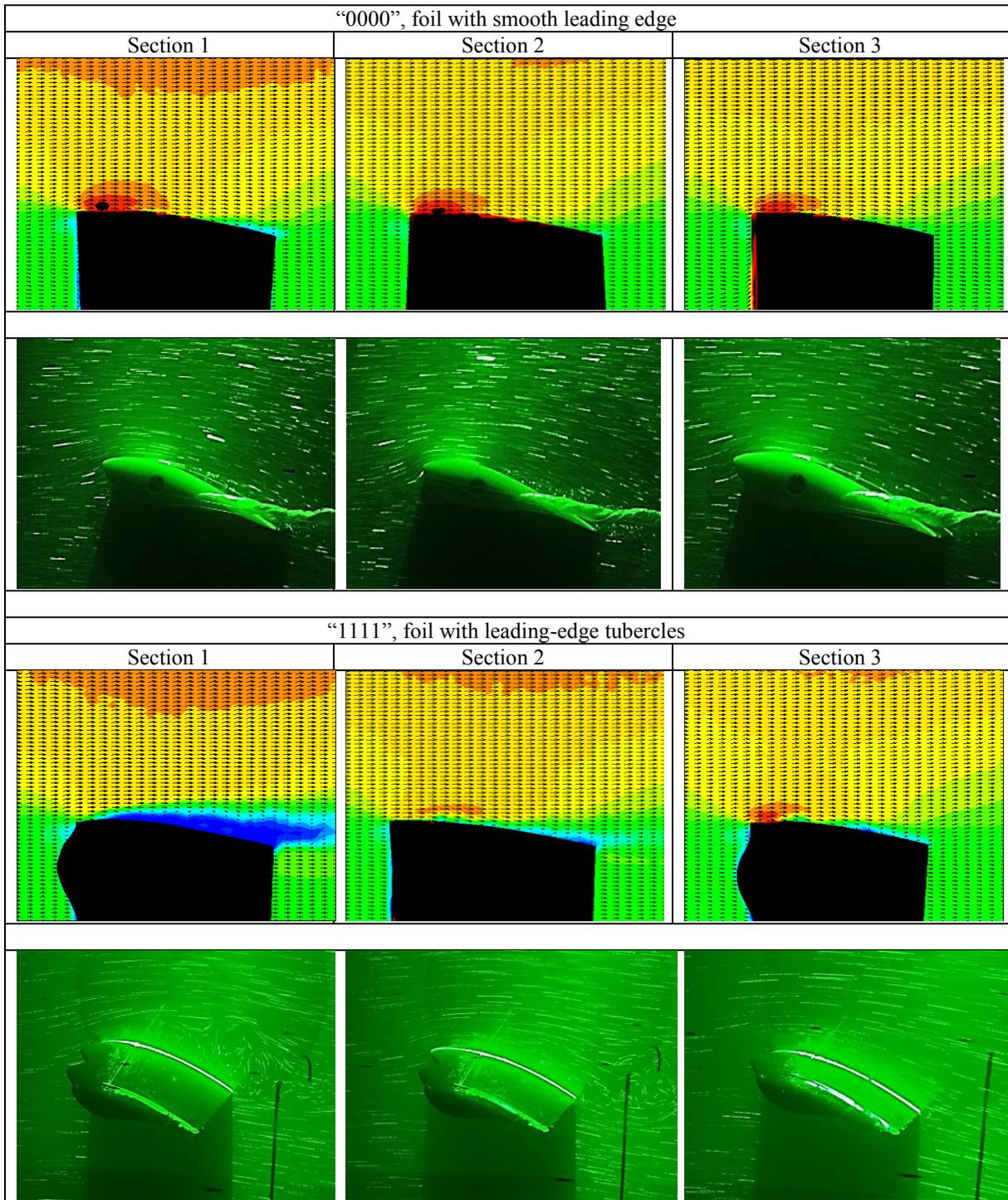
Table 2 Specifications of Dantec Dynamics Stereo PIV (Particle Image Velocimetry) system

Laser	NewWave Pegasus
Wavelength	527nm
Repetition rate per head	1-10K Hz; 2-20K Hz
Energy –Dual Cavity System	10 mJ @ 2000 Hz
Light sheet optics	80x70 high power Nd:YAG light sheet series
Synchronizer	NI PCI-6601 timer board
Camera	NanoSense MK III
Sensor size	1280x1024 pixels
Maximum capture frequency	1000Hz
Maximum images	3300
Seeding particles	Talisman 30 white 110 plastic powder

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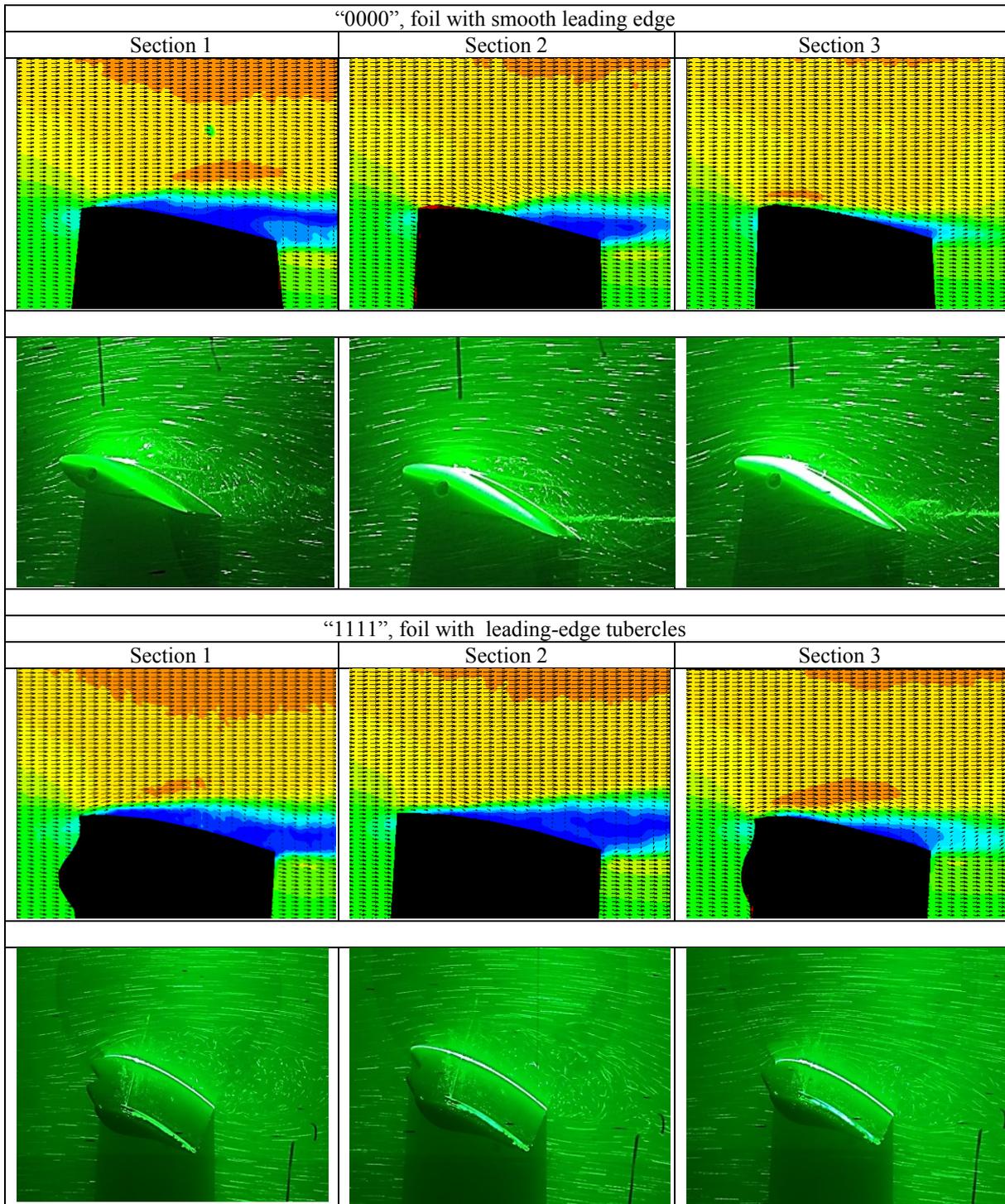
Table 3 Comparative experimental flow patterns at 3 selected sections for Foil "0000" and Foil "1111" observed at 16° of angle of attack



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Table 4 Comparative experimental flow patterns at 3 selected sections for Foil "0000" and Foil "1111" observed at 24° of angle of attack



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