PRELIMINARY EXPERIMENTAL ASSESSMENT OF THE PERFORMANCE OF ROTOR-ONLY AXIAL FANS DESIGNED WITH DIFFERENT VORTEX CRITERIA

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ABSTRACT

Rotor-only axial fans feature rotors designed according to different vortex criteria. Nowadays the literature does not exhaustively clarify when a specific swirl distribution has to be used and which are the advantages/drawbacks in terms of fan performance and efficiency. A review of the experimental performance of rotor-only axial fans designed with different vortex criteria is summarized here in $\Phi - \Psi$ and $\sigma - \delta$ (specific speed - specific diameter) graphs to identify the best operating conditions of each design. Four rotor-only axial fans (two free-vortex, a constant-swirl and a rigid-body swirl one) are tested on an ISO-5801-A rig. For two of them, flow velocities at rotor exit are measured with a 5-hole probe. The result is an experimentally based map around the Cordier curve for rotor-only axial fans. Indications on the best $\Phi - \Psi$ range for fans designed using different vortex criteria are provided and explained. The effects of increasing the tip clearance on the rotor performance at design duty are investigated as well.

KEYWORDS

Rotor-only axial fans, Vortex criteria, Axial-fan design, Arbitrary vortex, Non-Free Vortex, Cordier curve

NOMENCLATURE

$\text{const}$ generic constant
$c$ chord length [mm]
$c_{\text{tip}}$ tip chord length [mm]
$r$ radius [m]
$R$ tip radius [m]
$tc$ tip clearance [mm]
$D$ fan diameter [m]
$b/c$ airfoil camber [%]
$T$ aerodynamic rotor torque [Nm]
$q_v$ flow-rate [$m^3$/s]
$c_u$ local swirl velocity [m/s]
$c_{a2}$ local axial velocity [m/s]
$c_a = \frac{q_v}{\pi \frac{D^2}{4} (1-\nu^2)}$ mean axial velocity [m/s]
$v_m = \frac{q_v}{\pi D^2 4}$ velocity at fan exit [m/s]
$n$ rotational speed [rpm]
$Re_{\text{tip}} = \frac{\nu (\pi D^2)}{\nu} \frac{D^2}{c_{\text{tip}}}$ Reynolds number
$DF$ Lieblein Diffusion Factor
$FVP = \frac{1}{2} \rho v_m^2$ fan velocity pressure [Pa]
$\Delta p_{t-s}$ fan total-to-static pressure rise [Pa]
\[ FTP = \Delta p_{t-s} + FVP \quad \text{fan total pressure [Pa]} \]

\[ \nu \quad \text{hub-to-tip ratio} \]

\[ \omega \quad \text{angular velocity [rad/s]} \]

\[ \Phi = \frac{q_v}{(\pi \frac{D}{2})(\pi \frac{D}{2})^2} \quad \text{flow-rate coefficient} \]

\[ \Psi = \frac{(FTP \text{ or } \Delta p_{t-s})}{\frac{1}{2}(\frac{\omega}{\pi})^2} \quad \text{pressure coefficient} \]

\[ \eta = \frac{(FTP \text{ or } \Delta p_{t-s})q_v}{\Gamma \omega} \quad \text{efficiency} \]

\[ \sigma = \frac{n \rho^0.5}{FTP} \quad \text{specific-speed} \]

\[ \delta = \frac{D \cdot FTP^{0.25}}{q_v^{0.5}} \quad \text{specific-diameter} \]

\[ \rho \quad \text{air mass density [kg/m}^3\text{]} \]

\[ \xi \quad \text{stagger angle (with respect to fan axis) [°]} \]

\[ \mu \quad \text{air dynamic viscosity [Pa s]} \]

\[ \Gamma \quad \text{circulation [m}^2\text{/s]} \]

\[ \Sigma_a = \frac{c_a}{c_u} \quad \text{dimensionless axial velocity} \]

\[ \epsilon_s = \frac{\omega}{c_u} \quad \text{dimensionless tangential velocity} \]

**INTRODUCTION**

In this paper the performance of 30 rotor-only axial fan designed according to different vortex criteria is analyzed with the aim of providing fan designers with indications on the suitable choice of swirl distribution for a given duty.

The rotor-only configuration is largely the most common for low-to-medium pressure-rise axial-fan applications. In this layout fixed vanes and diffuser are absent and the only aerodynamic components are the impeller and the external casing. The resulting simplicity corresponds to cheapness of purchase and maintenance but it is paid with the loss of the dynamic pressures associated with the axial and tangential velocities at rotor exit (except the small amounts converted to static pressure with natural diffusion). According to the specific duty, rotor-only axial fans feature blades designed according to different swirl distributions. There are infinite possible distribution of swirl velocity \( c_u \) along the span. However, a schematic representation of the different blade shapes resulting from the most commonly used vortex criteria in fan design is reported in Fig. 1. Although several authors proposed design methods to obtain fan blades with span-wise variation of circulation (e.g., Kahane (1947), Downie et al. (1993)), quantitative indications on the best operational conditions for a particular swirl distribution are quite rare. Furthermore, even if it is certain that shifting from the free-vortex distribution to non-free-vortex ones with \( \omega \) increasing along the span allows to achieve higher pressure-rises, the literature is still ambiguous in stating which are the drawbacks in terms of overall fan efficiency. This work is aimed at providing indications on these aspects.

On the basis of the work by Ruden (1944), Kahane (1947) designed and tested two Non-Free-Vortex (NFV) rotor-only axial fans of high hub-to-tip ratio (\( \nu = 0.69 \)). The first rotor was designed using a quasi-Constant-Swirl (CS) distribution (i.e., with the tangential velocity \( c_u \simeq \text{const} \)) and the second using a Rigid-Body (RB) one (i.e., \( c_u = \text{const} \cdot r \)). Kahane states that “[..] spanwise load distributions differing from the free-vortex type may be desirable for designs in which a high-pressure-rise-rotor is required”. On the contrary, Wallis (1983) indicates arbitrary-vortex design to be suitable for low hub-to-tip ratio rotor-only fans with relatively demanding pressure-rise requirements (e.g., for cooling-tower applications), in particular to reduce the aerodynamic loading close to the hub to avoid blade overlapping. Wallis (p. 416) reports that efficiencies similar to those of free-vortex rotors are achievable. Downie et al. (1993) validated Wallis’ design method on three rotors having \( \nu = 0.38 \), one of which featuring a quasi-CS distribution and a total-to-static efficiency at design-point (DP) of \( \sim 47% \). More recently, Pascu (2009) applied an optimization algorithm on an existing \( \nu = 0.5 \) rotor for engine cooling purpose; the resulting geometry features a parabolic-increasing loading along the span and achieves a total-to-static efficiency of 46%. However, NFV distributions are applied
**Free-vortex:** tapered blade, highly twisted

**Arbitrary-vortex:** approximately constant chord, low twist

**Forced-vortex:** chord length span-wise increasing, low twist

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**Figure 1:** Schematic representation of the blade shapes deriving from the application of different spanwise gradients of circulation; adapted from Cory (2010).

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on high hub-to-tip ratio rotors as well (e.g., Vad, (2013)).

In this heterogeneous panorama few indications are given on the suitable operational conditions of NFV rotors. Vad (2010) reports that NFV designs are suitable for fans of small diameter, low blade count, and low rotor speed that operate at high flow-rate and/or total pressure rise. Bamberger (2015) gives quantitative support to this statement presenting $\sigma - \delta$ (specific speed and diameter) charts obtained with CFD-trained meta-models on optimized geometries: NFV geometries are suitable for operational conditions that lie below the well-known Cordier curve (i.e., at relatively low $\sigma - \delta$ combinations). However, the highest total-to-static efficiencies for rotor-only fans are obtained with free-vortex designs lying on the Cordier line. Nonetheless, nowadays a clear experimentally-based picture of the duty points of rotor-only fans designed according to different vortex criteria is still not available (e.g., Pascu (2009)).

In this work a literature analysis on rotor-only axial fans that feature blades designed with different vortex criteria is performed. Fans’ performance at the design point $DP$ (or best-efficiency point $BEP$, when $DP$ is not declared) are organized in $\Phi - \Psi$ and $\sigma - \delta$ graphs. The result is an experimentally based map around the Cordier curve for rotor-only fans. Furthermore, $\eta - \Psi$ graphs are presented for a range of the flow-coefficient, to provide a good overview of the suitable operational range of each swirl distribution. According to the standard (ISO, 2011), pressure rise and efficiency of each fan are reported both as total-to-static and fan total pressure terms. The rotors have been subdivided in three macro groups, according to the simplified classification of Fig. 1: Free-Vortex ($FV$) rotors (i.e., $c_u = \text{const}$) and Forced-Vortex ($ForV$, i.e., all the $c_u$ distributions that increase along the span) at the two opposite sides, with Arbitrary-Vortex ($AV$) rotors lying somehow in between, ranging from span-wise linearly decreasing $c_u(r)$ distributions to constant $c_u$ (i.e., constant-swirl). To corroborate the indications obtained from this literature analysis, four rotor-only fans are tested on an ISO 5801 inlet chamber rig: the performance of two FV fans featuring $\nu = 0.44$ and $\nu \sim 0.64$, respectively, are compared to those of a CS rotor with $\nu = 0.44$ and a RB rotor with $\nu = 0.31$. For the last two rotors, local values of flow velocities are measured with a 5-hole probe at the rotor exit in order to have more detail on the flow field of NFV designs.

The losses of fan performance due to the increase of the tip clearance are investigated as well. As industrial fans are likely to operate at relevant magnitudes of $\frac{tc}{D}$ (ratio of tip-clearance $tc$ over external duct diameter $D$), designers need to be aware of the performance losses associated
with the specific vortex criteria. Accordingly, tests are performed on the fans under investigation at different tip-gaps to clarify the amount of the losses in terms of pressure rise and efficiency at DP due to the increase of tip clearance for different swirl distributions.

The results presented in this work can provide fan designers with clear and quantitative indications on the choice of the swirl distribution for rotor-only axial fans as well as on the expected penalties at design duty related to an increase of the tip-gap.

OVERVIEW ON ROTOR-ONLY PERFORMANCE

In case of rotor-only fans the total-to-total pressure-rise delivered to the fluid differs from the fan total pressure rise \( FTP \) (see ISO, 2011), as the standard considers the dynamic pressure associated with the tangential velocity at the rotor outlet completely dissipated. Accordingly, most of the authors are used to present fan characteristics in terms of total-to-static pressure rise \( \Delta p_{t-s} \) and efficiency \( \eta_{t-s} \). To avoid any ambiguity and in accordance with the ISO standard (2011), fans performance are presented in the following both in terms of fan total pressure \( FTP \) and total-to-static one. Whether necessary, \( FTP \) values have been computed according to Eq. 1:

\[
FTP = \Delta p_{t-s} + FVP = \Delta p_{t-s} + \frac{1}{2} \rho \cdot v_{m}^2 \ [Pa]
\]  

where the Fan Velocity Pressure \( FVP \) is related to the average meridional component of the velocity at fan exit. Notice that specific speed \( \sigma \) and diameter \( \delta \) are computed using \( FTP \). Only rotor-only fans with no diffuser at the fan outlet are considered in this review.

Classification and assumptions

As stated in the Introduction, fans of different swirl distributions have been grouped according to the three macro categories identified in Fig. 1. Experimental data at fan design-point were considered; when DP was not declared, the fan performance at BEP was considered. The data of the fans are reported in the Tab. 1 (refer to the Nomenclature for the definition of each term). To avoid misunderstandings some clarifications are necessary: i) as many impellers feature small tip-clearances, the internal diameter of the casing is considered the fan diameter \( D \); ii) the Reynolds number \( Re_{tip} \) is computed on \( c_{tip} \) and on the tip rotational speed \( \omega \cdot R \). Whether the chord length at the tip was not declared this value has been estimated by analyzing the pictures of the rotors. Because of the high stagger angles at the tip, \( c_{tip} \) is considered approximately equal to the projected length estimated from the front picture of the rotor. This approach introduces a slight uncertainty on the computation of \( Re_{tip} \). According to Carter et al. (1960) most of the fans performance reported in Table 1 are not significantly affected by Reynolds number effects. However, for the fans that feature \( Re_{tip} < 10^5 \) some efficiency penalties are expected.

Fans were easily classified when the swirl distribution was indicated. When \textit{quasi-} is reported in front of the vortex distribution it is meant that the blade design mostly resembles the related one (e.g., \textit{quasi-CS} means that the swirl distribution is approaching the span-wise constant one). Whenever the vortex-design-criteria was not declared, different approaches were taken (observation of the span-wise velocity distributions at rotor outlet, cross-reference with other articles of the same author, CFD analysis, and, eventually, analysis of the blade shape). However, some degree of uncertainty in distinguishing free-vortex rotors from arbitrary-vortex ones with span-wise decreasing \( c_{u}(r) \) is unavoidable. Whenever air density is not specified in the reference, it has been assumed equal to \( 1.2 \text{ kg/m}^3 \).
Table 1: Rotor-only experimental data at design point or best efficiency. (*) Estimated.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Vortex</th>
<th>( \Phi )</th>
<th>( \nu )</th>
<th>( \Psi_{FTP} )</th>
<th>( \eta_{FTP} )</th>
<th>( \sigma )</th>
<th>( \delta )</th>
<th>( \Psi_{f-s} )</th>
<th>( \eta_{f-s} )</th>
<th>( Re_{tip} )</th>
<th>( \frac{\psi}{\psi_u} ) [%]</th>
<th>NOTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peck &amp; Ross, in Stepanoff (1955)</td>
<td>FV(*)</td>
<td>0.182</td>
<td>0.4</td>
<td>0.169</td>
<td>71%</td>
<td>1.620</td>
<td>1.503</td>
<td>0.136</td>
<td>57%</td>
<td>-</td>
<td>-</td>
<td>Rotor-only case</td>
</tr>
<tr>
<td>Pistolesi (1924)</td>
<td>FV</td>
<td>0.221</td>
<td>~0.18</td>
<td>0.101</td>
<td>77%</td>
<td>2.633</td>
<td>1.198</td>
<td>0.052</td>
<td>40%</td>
<td>3.86e5</td>
<td>0.1</td>
<td>constant-chord</td>
</tr>
<tr>
<td>Bamberger (2015)</td>
<td>quasi-FV</td>
<td>0.215</td>
<td>0.3</td>
<td>0.116</td>
<td>74%</td>
<td>2.329</td>
<td>1.259</td>
<td>0.070</td>
<td>44%</td>
<td>~2.00e5</td>
<td>0.1</td>
<td>DP3 rotor</td>
</tr>
<tr>
<td>Bamberger (2015)</td>
<td>quasi-FV</td>
<td>0.173</td>
<td>0.4</td>
<td>0.236</td>
<td>68%</td>
<td>1.229</td>
<td>1.676</td>
<td>0.206</td>
<td>59%</td>
<td>2.64e5</td>
<td>0.1</td>
<td>DP2 rotor</td>
</tr>
<tr>
<td>FV-1</td>
<td>FV</td>
<td>0.23</td>
<td>0.44</td>
<td>0.187</td>
<td>60%</td>
<td>1.686</td>
<td>1.371</td>
<td>0.133</td>
<td>41%</td>
<td>5.20e4</td>
<td>0.5</td>
<td>low ( Re_{tip} )</td>
</tr>
<tr>
<td>FV-2</td>
<td>FV</td>
<td>0.2</td>
<td>~0.64</td>
<td>0.228</td>
<td>42%</td>
<td>1.335</td>
<td>1.545</td>
<td>0.188</td>
<td>36%</td>
<td>1.25e5</td>
<td>0.5</td>
<td>no inlet spinner</td>
</tr>
<tr>
<td>FV-3</td>
<td>FV</td>
<td>0.23</td>
<td>0.33</td>
<td>0.092</td>
<td>61%</td>
<td>2.871</td>
<td>1.148</td>
<td>0.04</td>
<td>25%</td>
<td>3.09e4</td>
<td>0.5</td>
<td>low ( Re_{tip} ), Unpubl. data</td>
</tr>
<tr>
<td>Venter (1990)</td>
<td>AV(*)</td>
<td>0.141</td>
<td>0.15</td>
<td>0.120</td>
<td>68%</td>
<td>1.845</td>
<td>1.565</td>
<td>0.100</td>
<td>57%</td>
<td>4.93e5</td>
<td>0.2</td>
<td>GH-fan</td>
</tr>
<tr>
<td>Louw et al. (2012)</td>
<td>AV</td>
<td>0.168</td>
<td>0.4</td>
<td>0.123</td>
<td>74%</td>
<td>1.971</td>
<td>1.445</td>
<td>0.103</td>
<td>62%</td>
<td>4.44e5</td>
<td>0.2</td>
<td>B1-fan</td>
</tr>
<tr>
<td>Beiler &amp; Carolus (2012)</td>
<td>AV(*)</td>
<td>0.222</td>
<td>0.5</td>
<td>0.229</td>
<td>64%</td>
<td>1.422</td>
<td>1.469</td>
<td>0.180</td>
<td>51%</td>
<td>2.09e5</td>
<td>0.3</td>
<td>opt. rotor</td>
</tr>
<tr>
<td>Bamberger &amp; Carolus (2012)</td>
<td>CS+FV</td>
<td>0.180</td>
<td>0.4</td>
<td>0.189</td>
<td>64%</td>
<td>1.478</td>
<td>1.555</td>
<td>0.160</td>
<td>54%</td>
<td>2.01e5</td>
<td>0.15</td>
<td>unswept rotor A</td>
</tr>
<tr>
<td>Beiler &amp; Carolus (1999)</td>
<td>CS</td>
<td>0.196</td>
<td>0.4</td>
<td>0.146</td>
<td>59%</td>
<td>1.869</td>
<td>1.398</td>
<td>0.108</td>
<td>44%</td>
<td>8.84e5</td>
<td>0.34</td>
<td>Mark-3 rotor</td>
</tr>
<tr>
<td>Downie et al. (1993)</td>
<td>quasi-CS</td>
<td>0.197</td>
<td>0.38</td>
<td>0.139</td>
<td>64%</td>
<td>1.954</td>
<td>1.375</td>
<td>0.101</td>
<td>47%</td>
<td>2.67e5</td>
<td>0.4</td>
<td>FV - 30% at hub, FV + 20% at tip</td>
</tr>
<tr>
<td>Corsini et al. (2016)</td>
<td>AV(*)</td>
<td>0.234</td>
<td>0.4</td>
<td>0.146</td>
<td>71%</td>
<td>2.038</td>
<td>1.286</td>
<td>0.092</td>
<td>45%</td>
<td>2.51e5</td>
<td>0.48</td>
<td>FV - 30% at hub, FV + 20% at tip</td>
</tr>
<tr>
<td>Masi et al. (2014)</td>
<td>quasi-CS</td>
<td>0.238</td>
<td>0.69</td>
<td>0.249</td>
<td>45%</td>
<td>1.382</td>
<td>1.449</td>
<td>0.193</td>
<td>35%</td>
<td>3.29e5</td>
<td>0.07</td>
<td>Fan 1; ( \frac{\psi}{\psi_u} ) &lt;~ 0 decr.</td>
</tr>
<tr>
<td>Kahane (1947)</td>
<td>quasi-CS</td>
<td>0.141</td>
<td>0.15</td>
<td>0.115</td>
<td>67%</td>
<td>1.899</td>
<td>1.550</td>
<td>0.095</td>
<td>55%</td>
<td>4.80e5</td>
<td>0.2</td>
<td>Fan 1</td>
</tr>
<tr>
<td>Venter (1990)</td>
<td>CS</td>
<td>0.174</td>
<td>0.29</td>
<td>0.238</td>
<td>68%</td>
<td>1.756</td>
<td>1.484</td>
<td>0.111</td>
<td>54%</td>
<td>2.08e5</td>
<td>0.66</td>
<td>V-fan</td>
</tr>
<tr>
<td>Nouri et al. (2012)</td>
<td>AV(*)</td>
<td>0.150</td>
<td>0.34</td>
<td>0.267</td>
<td>46%</td>
<td>1.416</td>
<td>1.676</td>
<td>0.155</td>
<td>40%</td>
<td>2.00e5</td>
<td>0.48</td>
<td>RR-rotor</td>
</tr>
<tr>
<td>Zayani et al. (2012)</td>
<td>AV</td>
<td>0.155</td>
<td>0.34</td>
<td>0.178</td>
<td>46%</td>
<td>1.065</td>
<td>1.580</td>
<td>0.296</td>
<td>39%</td>
<td>3.29e5</td>
<td>0.07</td>
<td>USK-rotor: ( \eta_{\tilde{f}}(?) )</td>
</tr>
<tr>
<td>Guedel et al. (2012)</td>
<td>AV(*)</td>
<td>0.150</td>
<td>0.34</td>
<td>0.178</td>
<td>46%</td>
<td>1.065</td>
<td>1.580</td>
<td>0.296</td>
<td>39%</td>
<td>3.29e5</td>
<td>0.07</td>
<td>USK-rotor: ( \eta_{\tilde{f}}(?) )</td>
</tr>
<tr>
<td>Eberlinc et al (2009)</td>
<td>ForV(*)</td>
<td>0.230</td>
<td>0.28</td>
<td>0.210</td>
<td>29%</td>
<td>1.546</td>
<td>1.412</td>
<td>0.157</td>
<td>22%</td>
<td>1.97e5</td>
<td>-</td>
<td>relevant tc</td>
</tr>
<tr>
<td>Nouri et al. (2012)</td>
<td>ForV</td>
<td>0.222</td>
<td>0.29</td>
<td>0.205</td>
<td>59%</td>
<td>1.546</td>
<td>1.429</td>
<td>0.156</td>
<td>45%</td>
<td>2.01e5</td>
<td>0.66</td>
<td>relevant tc</td>
</tr>
<tr>
<td>Lindemann et al. (2014)</td>
<td>ForV</td>
<td>0.240</td>
<td>0.2</td>
<td>0.230</td>
<td>60%</td>
<td>1.476</td>
<td>1.413</td>
<td>0.175</td>
<td>46%</td>
<td>4.50e5</td>
<td>0.6</td>
<td>Fan1.1; relevant tc</td>
</tr>
<tr>
<td>Lindemann et al. (2014)</td>
<td>ForV</td>
<td>0.207</td>
<td>0.2</td>
<td>0.247</td>
<td>62%</td>
<td>1.233</td>
<td>1.571</td>
<td>0.225</td>
<td>52%</td>
<td>4.50e5</td>
<td>0.6</td>
<td>Fan2.2; relevant tc</td>
</tr>
<tr>
<td>Pascu (2009)</td>
<td>Parabolic</td>
<td>0.185</td>
<td>0.53</td>
<td>0.274</td>
<td>53%</td>
<td>1.134</td>
<td>1.684</td>
<td>0.240</td>
<td>46%</td>
<td>9.95e5</td>
<td>0.18</td>
<td>( \nu ) constrained</td>
</tr>
<tr>
<td>Kahane (1947)</td>
<td>RB</td>
<td>0.238</td>
<td>0.69</td>
<td>0.353</td>
<td>47%</td>
<td>1.065</td>
<td>1.580</td>
<td>0.296</td>
<td>39%</td>
<td>3.29e5</td>
<td>0.07</td>
<td>Fan 2</td>
</tr>
<tr>
<td>RB</td>
<td>RB</td>
<td>0.314</td>
<td>0.337</td>
<td>0.210</td>
<td>62%</td>
<td>1.710</td>
<td>1.230</td>
<td>0.127</td>
<td>35%</td>
<td>1.12e5</td>
<td>0.6</td>
<td>tip affected</td>
</tr>
</tbody>
</table>
Performance charts

The performance of the fans in Tab. 1 has been organized in the graphs of Figure 2. It must be noticed that free-vortex fans are not numerous in the rotor-only configuration, while arbitrary-vortex rotors are by far the largest group (e.g., Wallis (1983)). From the $\Phi - \Psi_{FTP}$ graph in Fig. 2a) it appears that forced-vortex fans operate at higher pressure and flow coefficients than the classical Cordier line (Lewis, (1996)), while most of the arbitrary-vortex fans show the opposite behavior (lower flow-rates and pressure rises). In Fig. 2b) the same performance are plotted in terms of $\sigma - \delta$ within the typical field of axial-fans (lower-efficiencies fans were not considered). Among the three classes, free-vortex best fits the Cordier-line while forced-vortex fans operate at lower $\sigma - \delta$ conditions, confirming what already observed by Bamberger (2015). However, most of high-efficiency arbitrary-vortex fans lie above the Cordier line (i.e., at higher flow-rates and lower pressure rises for a given diameter and rotational speed), thus confirming the qualitative indications reported by Wallis (1983). It must be noticed that, regardless of the vortex-criteria, $\eta_{FTP}$ at BEP/DP are slightly affected by the value of the corresponding flow-coefficient (Masi et al., 2016): most efficient fans ($\eta_{FTP}$ between 60% and 77%) feature flow-coefficients $\Phi$ ranging between 0.12 and 0.31 (see Tab. 1). Instead, total-to-static efficiencies show a marked decrease as the flow-coefficient increases (see Tab. 1).

The performance of fans with flow-coefficient $\Phi = 0.21 \pm 0.03$ was considered in Fig. 3 to provide an immediate comparison of the different vortex criteria at similar $\Phi^1$. Hub-to-tip ratios are reported as well, to relate fan geometry with the vortex-distribution and operating condition. A marked decrease of $\eta_{FTP}$ with the pressure-coefficient is observed in Fig. 3a). This trend was expected, as at larger pressure-rises the flow deflection is higher and so is the dissipation of the dynamic pressure associated with the tangential velocity (that cannot be converted to static pressure because of the absence of straightener). Highest fan total efficiencies are achieved by FV rotor-only axial fans of low pressure rise coefficients ($\Psi_{FTP} \sim 0.1$) and low hub-to-tip ratio ($\nu \sim 0.2 - 0.3$). On the opposite side, forced-vortex fans achieve relevant pressure coefficients ($\Psi_{FTP} \geq 0.23$) at lower efficiencies. However, rotor-straightener fans may achieve $\Psi_{FTP} \geq 0.24$, with $\eta_{FTP} = 0.79$ (e.g., Osborne (1966)). Accordingly, the application of forced-vortex criteria seems to be proper only when some constraints exist (e.g., dimensional limits on fan longitudinal length). Arbitrary-vortex fans of decreasing swirl distribution (rotors with $\nu = 0.4$ and 0.45) reach peak efficiencies similar to the highest $\eta_{FTP}$ of the free-vortex rotors, confirming what already stated by Wallis (1983). In Fig. 3b) the total-to-static $\eta_{t-s}$ plots are reported as well. However, trends in this figure might be misleading because of the important effect of flow-rate on total-to-static efficiency.

FANS UNDER TEST AND EXPERIMENTAL APPARATUS

The 315 mm fans considered for the experimental tests are named FV-1, FV-2, CS, and RB (Fig. 4); the main geometrical parameters are reported in Tab. 2. All rotors feature quite low hub-to-tip ratios, except the FV-2 one that was originally intended for a high pressure-rise rotor-straightener application. This rotor is considered within this work to provide further data of limited availability on rotor-only fans with relevant $\nu$ ratio. The fans feature 3D printed blades, except for the RB one which was injection-molded for serial production. In particular, this last rotor was originally intended for a 300 mm application. As the duct diameter of the test

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1One of the forced-vortex fan (Eberlinc et al., 2009) was not considered in Fig. 3 because of an uncommon low efficiency.
Figure 2: Performance of rotor-only fans at DP or BEP for different vortex criteria: FV (Δ), AV (○), ForV (◇); a) flow coefficient versus fan total pressure coefficient (Φ – Ψ<sub>FTP</sub>) chart, b) specific speed versus specific diameter (σ – δ) chart. Note that only high-efficiency fans were reported in Fig. b). Cross markers (×) indicate the fans tested within this work.

rig is 315 mm, the blade span was increased taping 2 mm-thick balsa-wood strips at the tip (see Fig. 4a), on the right). Although this modification was carefully made, some detrimental effects on fan efficiency were unavoidable. All the fans feature NACA-65 airfoils (properly modified in the RB rotor for molding necessities). Both FV-1 and FV-2 fans feature highly twisted blades, while twist is limited for the two NFV rotors (see Tab. 2). FV-1 and CS fans share the same aluminum alloy hub. Tip clearance <i>tc</i> is the same for all fans (1.5 mm) except for the RB one (~1.8 mm). The CS and RB rotors were tested at several values of <i>tc</i>, as well. The characteristic curves were obtained at the design blade positioning angle (with respect to the rotor plane) that
Figure 3: Relations between rotor geometries (ν), vortex-criteria and fan performance for rotors of similar flow-rate coefficients (0.18 < Φ < 0.24); a) fan total pressure parameters (FTP), b) total-to-static parameters (t-s)

Table 2: Geometrical parameters of the fan blades tested. Angles and chord length rounded to integer values. Values computed with local velocities on cylindrical surfaces.

<table>
<thead>
<tr>
<th></th>
<th>ν</th>
<th>n [rpm]</th>
<th>ξ [°]</th>
<th>$\mu$ [%]</th>
<th>c [mm]</th>
<th>$\bar{D}F^2$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>hub</td>
<td>tip</td>
<td>hub</td>
<td>tip</td>
<td>hub</td>
</tr>
<tr>
<td>FV-1</td>
<td>0.44</td>
<td>1350</td>
<td>37</td>
<td>65</td>
<td>7.7</td>
<td>4.0</td>
</tr>
<tr>
<td>FV-2</td>
<td>0.64</td>
<td>950</td>
<td>43</td>
<td>61</td>
<td>7.7</td>
<td>3.3</td>
</tr>
<tr>
<td>CS</td>
<td>0.44</td>
<td>1350</td>
<td>40</td>
<td>63</td>
<td>4.7</td>
<td>4.7</td>
</tr>
<tr>
<td>RB</td>
<td>0.31</td>
<td>720</td>
<td>30</td>
<td>68</td>
<td>6.5</td>
<td>6.5</td>
</tr>
</tbody>
</table>

is 24.6°, 29.4°, 28°, 32° for FV-1, FV-2, CS and RB, respectively. All fans share the same external duct and bell-mouth inlet. A cylindrical mock-up of the electrical motor (having a 127 mm diameter) and the relative struts are positioned in front of the rotors (i.e., on the inlet side).
Fan performance was measured according to the ISO standard (2011). The inlet chamber test rig is visible in Fig. 4b). Static pressures were measured using water micro-manometers (±0.1 Pa). Measurement uncertainty is estimated to be < 2% for the total-to-static pressure and flow-rates measurements. The Impeller efficiency (see ISO (2011)) was obtained by measuring the rotor torque $T$ and rotational speed $n$. The aerodynamic torque $T$ was measured with a torque-table dynamometer, according to the ISO standard (2011, p.25). The friction torque due to the ball bearings and the flexible coupling was measured before and after each test. The average value of friction torque was subtracted to gross data measured during the fan test to obtain the aerodynamic torque $T$ (see ISO (2011), p.26). Although the measurement method agrees with the standard, some dispersion of the data due to the low torque values involved ($\sim 0.1$ Nm) was observed. Accordingly, each test was repeated up to three times to reduce the uncertainty on the measured efficiencies up to $\sim 4\%$. Woolen tufts were positioned at the rotor exit to visualize the flow field (see Fig. 4, right). Measures of local flow velocities and angle at the rotor exit were taken with a 5-hole United Sensor DA-187 probe. The probe was positioned at the duct exit, 5 cm downwind of the rotor plane (see Fig. 4c)); the uncertainty with the radial direction was limited to $\pm 0.1^\circ$. The distance from the rotor outlet section allowed to perform measurements on a flow field at radial equilibrium in the main part of the blade span. In fact, the tufts showed three-dimensional effects only close to the hub region (see the inner tuft in Fig. 4c)). Flow angle and total pressure measurements at five span-wise positions (20%, 35%, 50%, 65% and 80% of the blade span) were obtained by averaging several measurements. Swirl and axial velocity distributions were computed assuming a static pressure equal to the atmospheric pressure.

RESULTS AND DISCUSSION

The characteristic curves of the four fans are shown in Fig. 5. The higher pressure rise allowed by NFV criteria can be well appreciated comparing the curves of FV-1, CS and RB fans. In particular, the increase in $\Psi_{FTP}$ at peak pressure is approximately 0.05 for the CS fan.
Figure 5: Characteristics of fans at blade design angles. 

- **a-c)** fan total pressure (FTP) performance,
- **b-d)** total-to-static performance (t-s),
- **e)** local velocities distributions at design flow rate.
and \( \sim 0.09 \) for the RB design. Similar increases hold for the total-to-static quantities as well. The extension of the flow coefficient range from peak efficiency to peak pressure (i.e., the stall margin) is another interesting feature to be compared. Data clearly show that: the higher the departure from the FV design, the higher the stall margin. The radial shift of the flow within the blade passage after the inception of the back-flow at the hub is responsible for the differences among the three vortex criteria, as was suggested by the tufts visualization. Indeed, the increase of the axial velocity component towards the blade tip decreases the local flow incidence of the blade sections and moves the stall towards lower flow-rates. This extension of the pressure-rise curve is important if the fan is installed in an air-system that features a marked variation of the resistance curve.

FV-1, CS, and RB fans feature similar efficiencies (\( \sim 60\% \)) that are considered quite satisfactory according to the relevant tip gap and the low \( Re_{tip} \) of these experiments. However, the specific speed and diameter of the CS fan (1.576 and 1.334, respectively) fall in the field of Forced-vortex fans according to Fig. 2b). In light of this, it is likely that a \( ForV \) rotor achieves higher efficiency at similar design conditions (see e.g., Lindemann (2014)).

The FV-2 rotor shows quite low efficiency, according to the lack of the straightener and diffuser provided in the original design. Furthermore, the absence of an inlet spinner is likely to play a role as well for such high hub-to-tip ratios (see e.g., Bamberger et al. (2015)). The FV-2 fan achieves a peak pressure coefficient equal to 0.225, halfway between the performance of FV-1, CS and RB.

The dimensionless velocities at the rotor outlet for the CS and RB fans at design duty are reported in Fig. 5 e). Wall-effects are visible for both fans at 20\% and 80\% span stations, although the trends observed mostly resemble the design ones.

The use of data obtained from fans featuring low Reynolds numbers and relevant tip clearances is a point of weakness of this research. Because of these issues, the magnitudes of the curves presented in Fig. 3 might slightly change and need to be confirmed. A sound experiment should compare fans of different vortex criteria running at high \( Re_{tip} \) (\( > 10^5 \)) and with small tip clearances (\( \sim 0.1 - 0.2\% \)). However, such an experiment is not available at present.

The detrimental effects on fan performance at design duty due to an increasing of the tip-clearance are investigated as well. The losses of pressure-rise and efficiency for NFV rotors are expected to be higher with respect to free-vortex ones (Wallis (1983), Vad (2002)). According to Wallis, the fan total efficiency losses \( \Delta \eta_{FTP} \) associated with the increase of \( tc \) for FV fans are given by Eq. 2:

\[
\Delta \eta_{FTP} = 2 \cdot \left( \frac{tc}{\text{blade span}} - 0.01 \right) \quad [-]
\]

According to authors’ best knowledge, Eq. 2 is the only correlation specific for free-vortex fans currently available. However, note that the efficiency loss computed with Eq. 2 is generally lower than the efficiency losses \( \Delta \eta \) provided for rotor-only fans of unspecified vortex design (see Eck (1973), p. 269). Although further investigations on the subject of tip clearance losses are required, the preliminary data from tests reported in the literature (e.g., Kahane (1947), Venter (1990)) and those performed on the CS and RB rotors suggest that fan performance decrease with the slopes reported in Tab. 3.
Table 3: Losses of fan pressure rise and efficiency due to the increase of tip clearance.

<table>
<thead>
<tr>
<th></th>
<th>$\Delta \Psi_{FTP}$</th>
<th>$\Delta \eta_{FTP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS</td>
<td>$-30.6 \cdot \frac{tc}{D}$</td>
<td>$-12.5 \cdot \frac{tc}{D}$</td>
</tr>
<tr>
<td>RB</td>
<td>$-30.3 \cdot \frac{tc}{D}$</td>
<td>$-30.5 \cdot \frac{tc}{D}$</td>
</tr>
</tbody>
</table>

CONCLUSIONS

The experimental performance of 30 rotor-only axial fans at design or best efficiency duty operation were surveyed. The different vortex criteria used to design these fans allow to show that:

- Free-vortex fans of low hub-to-tip ratios ($\nu = 0.2 - 0.3$) achieve the highest fan total efficiency (up to 77%) at low pressure-rise coefficients ($\Psi_{FTP} \sim 0.1$);

- Rotors with span-wise decreasing swirl distribution achieve relevant fan total efficiency ($\sim 72\%$) at pressure-rises higher than free-vortex design for corresponding flow-rate coefficient ($\Psi_{FTP} \sim 0.18$);

- Forced-vortex fans are suitable for high flow coefficients ($\Phi > 0.2$) and high pressure coefficient ($\Psi_{FTP} > 0.2$). Fan total efficiencies up to 62% are achievable, suggesting that forced-vortex rotors are an effective solution for applications where the available axial length of the fan is limited (e.g. air-conditioner external units);

In addition, the tests and local measurements performed on four rotor-only fans featuring different vortex criteria (two free-vortex, a constant-swirl and a rigid-body one) show that:

- NFV design extends the stall margin of free-vortex criterion because of the more favourable aerodynamic operation of the outer blade sections after inception of back-flow at the hub;

- This advantage of NFV design is counteracted by a sensitivity to blade tip clearance higher than free-vortex design;

- Forced-vortex design resulted the criterion most affected by an increase of the tip gap. Preliminary data show that the slope of fan total efficiency reduction due to tip clearance increase is about 4 times the corresponding value suggested for free-vortex design.

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REFERENCES


Ruden, P. (1944). Investigation of single stage axial fans. NACA TM No. 1062


