The case for advanced 3D design of ventilation fans - *overcoming the cost of capital*

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ABSTRACT

Fans that approach 90% total aerodynamic efficiency are feasible using advanced three-dimensional design features developed with the aid of computational fluid dynamics. In practice, however, many compromises have to be made in order to cost effectively manufacture the fan which limits the achievable efficiencies, increasing operational costs and raising the environmental impact. While the rotor blade is cast to accommodate complex aerodynamic profiles and the hub fixing; the stator vanes are generally fabricated. This leaves the designer with relatively few options when it comes to the design of the stator components. Two designs from Air Blow Fans, one primary and one secondary, featuring advanced 3D design of the rotor combined with advanced design of the stators and their more easily manufactured equivalents with simplified stators are compared in terms of performance and cost. The aim being to establish if and where these more advanced and costly designs might become viable alternatives to industry.

1. INTRODUCTION

Air Blow Fans is currently developing a new family of fan designs for the ventilation market that will take advantage of a number of advanced aerodynamic design features to enable high efficiencies and hence lower operational cost. For the rotor blades this means that any features that can be cast, are feasible. This includes a twist distribution and bowing over a limited span of the blade to reduce corner stall on the suction side of the blade at the hub, boundary layer trips and tubercules to assist with maintaining flow attachment across a greater range of flow rates and back pressures as well as forward sweep to ease the loading on the blade puck. All of these physical features have to be tailored to allow for the blade family to fit a wide variety of casing diameters operating off the same hub and with variable setting angles. Very few of these features can however, be utilized on the fabricated stator components that follow downstream of the rotor blades, and yet these stators are, arguably, more critical to the performance of the fan than the rotor blades. Operating as they do in an adverse pressure gradient and with relatively low speed flows while being required to turn the flow through large angles at the hub in particular is a challenging expectation.

This has led to the adoption of a tandem exit stator arrangement at Air Blow Fans where the plate support vanes at the back of the barrel are utilized to provide turning and eliminate exit swirl while the aerofoil main stators are used to achieve a broader operating range but are less highly loaded leading to improved performance overall.

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In this paper we will examine the design of the stator in more detail and look at alternative means of reducing flow separation and gaining efficiency over a broader operating range in two designs. The first is a 2m primary fan with limited installation space in terms of length. In this case we will examine the effect of bowing in the stator which would lead to the need to either cast or machine the stators, but offer excellent performance with reductions in the fan length. The second is a case from the new range of secondary fans, in this case a 40" (1016mm) fan with tandem stators, where we will examine the effects of twist in the stators. A two-dimensional or untwisted stators is simple to manufacture but restricts the fan's efficient operational range while a three-dimensional, twisted stator can increase the useful operational range of a fan to setting angles exceeding 30° from the nominal.

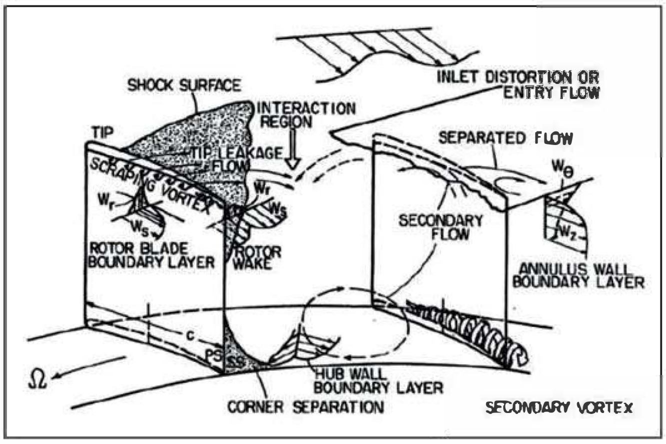

Figure 1. The nature of flow in an axial compressor rotor passage (Lakshiminarayana, 1996)

2. BOW AND TWIST

Various three-dimensional modifications to turbomachine blading have been intensely examined by the gas turbine community. The first of these is twist. It is hard to believe but prior to the early work on jet engines by Frank Whittle (Whittle, 1955) no one had thought to twist the blade to accommodate for the variation in circumferential velocities with radius change. Whittle is not only the father of the modern jet engine but also the inventor of the well-known free vortex method of twisting blades that applies equally to both compressors (or fans) and turbines.

In the world of turbines, it is common to adjust the localised twist of the blade in order to alter the work distribution produced in the rotor or increase the product of radius and outlet absolute tangential velocity at midspan and to alleviate secondary or loss generating flows in both stators and rotors (Lampart, et al., 1999 and Watanabe and Harada, 1999). In compressors or fans, where the pressure gradients adversely affect the onset of secondary flows the turning angles are milder to compensate, however, localized twist remains a method to reduce corner separation (see Error! Reference source not found.), otherwise known as corner stall at the hub. In the stator row localized twist can be used in the same manner, but in addition the twist can be used to compensate for any off-design radial variation in the flow angle emerging from the rotor row.

Bow, is also known as dihedral or compound lean in the literature and has been studied in compressors since the 1990s to address corner stall mechanisms that had been identified in the 1980s. Weingold, et al., 1997 describes the design of a compound bowed stator designed to reduce corner stall and the resulting flow blockage in the compressor achieving more than 1% efficiency improvement. Weingold et al. 1997, describe bowing as reducing diffusion rates in the suction surface corner and delaying or eliminating the formation of corner separation.

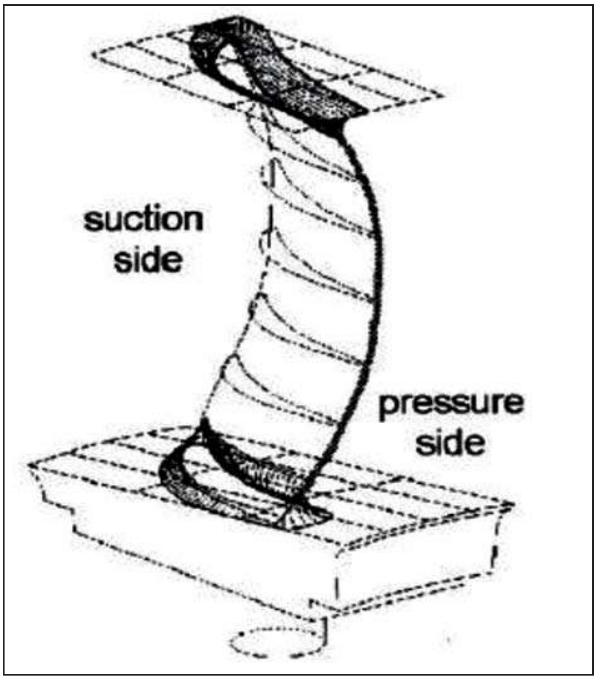

Figure 2. A heavily bowed Stator after Fischer, 2004

Sasaki 1998, showed that bowing increased loading at midspan and that dihedral made the blade row relatively insensitive to incidence compared to sweep. Gallimore et al. 2002 a & b report a 5% pressure increase over the entire speed line for a 3D optimized multistage compressor utilizing free form sweep and bow with the rotors largely utilizing sweep and the stators, compound bow, limited to hub and tip. Fischer, 2004 applied strong bowing, 30° at tip and 35° at the hub, to the stators of a 4-stage compressor and achieved a 1.4% increase in pressure which was ascribed to the shift of flow towards the midspan and the reduction of corner separation as a result.

3. CASE 1: 2M PRIMARY – EFFECT OF STATOR BOW

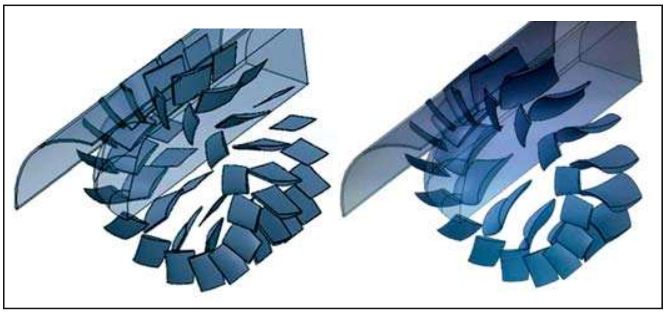

Figure 3. Final Tandem stator design (left), bowed stator design (right)

In this case the fan design came with two classes of constraint – the usual performance requirements of flow and pressure, but also the requirements of fitting within a given axial length as a result of space constraints.

At Air Blow Fans the design procedure for a primary fan starts with a optimizing the rotor blade such that it is fit for purpose using CFD analyses and meets the power demand requirement and minimizes loss generating flows as far as possible. Thereafter the stator is optimized to generated a blade with the corrected leading-edge incidence from hub to tip firstly and then to use localized twist and 3D effects to reduce loss generating secondary flows such as corner stall and to reduce noise by leaning the blade where possible to eliminate the possibility of wake interactions between rotor and stator.

In this particular case the pressure rise requirements resulted in a particularly strong corner separation on the hub suction side of the stator. Lean and increased chord have an effect and moderate bow did not had no effect. The final attempt to eliminate the corner stall was made using a strongly bowed stator (the bow radius was 3 times the span). The bowed stator is pictured above (Figure 3) and successfully eliminated corner stall and did so in a single row achieving exit swirl values lower than 5°.

Ultimately this design was eliminated as a result of manufacturing concerns and costs and replaced with a tandem arrangement utilizing the plate supports as a second turning vane to eliminate swirl while the aerofoil 1st stator vane provides efficiency at off design angles and has the load requirement reduced to remove corner stall.

The fan performance with the two different stator types can be seen in but this comes with an increase in power input making the total efficiencies almost equivalent. Secondly the bowed stators are less sensitive to off-design flows which is a consistent feature mentioned in the literature. In this case however it is unlikely that the fan would be operated at setting angle and flow rate combinations where this off-design advantage would be utilized.

While the bowed stator is slightly less efficient than the tandem design at peak efficiency it should be remembered that the stator chord and blade count has not seen as much optimization as that of the tandem row.

Ultimately the length constraint resulted in the diffuser cone having to be moved forward to start at the leading edge of the second stator (combined plate support) of the tandem design and this resulted in a 5% efficiency deficit at the design point as the combined diffusion of the vane turning and the diffuser cone results in a small degree of corner separation on the first stator undoing all the careful aerodynamic design on the blading.

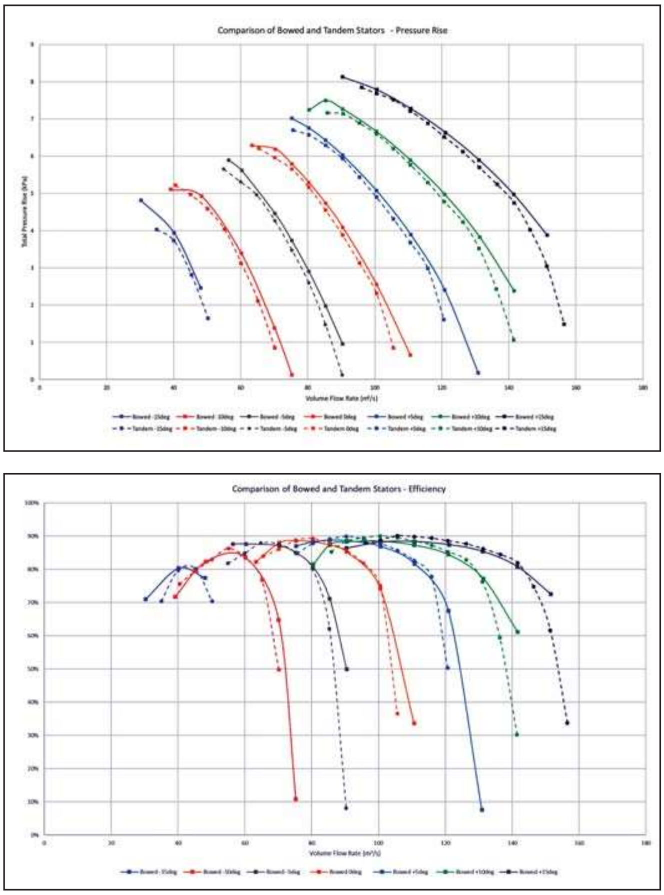

Figure 4. 2m Comparison of primary fan performance (top) and efficiency variation (bottom) between bowed and tandem stators

4. CASE 2: 40" SECONDARY – EFFECT OF STATOR TWIST

The performance of a fan in terms of efficiency is highly dependent on the performance of the stator row immediately following the rotor. While the total power input is dependent entirely on the rotor design, it is the diffusion through the stator row(s) that determines the final pressure recovery and hence efficiency.

In this second example a fan with a twisted 3D tandem stator set will be compared to a traditional (for mining secondary / auxillary fans) straight, untwisted stator fabricated from two rolled plates and a similarly constructed rolled plate tandem row. This difference is illustrated in Figure 5. This 2D stator profile is designed for the correct incidence at the hub at the design flow rate. The stators have similar chord and thickness,

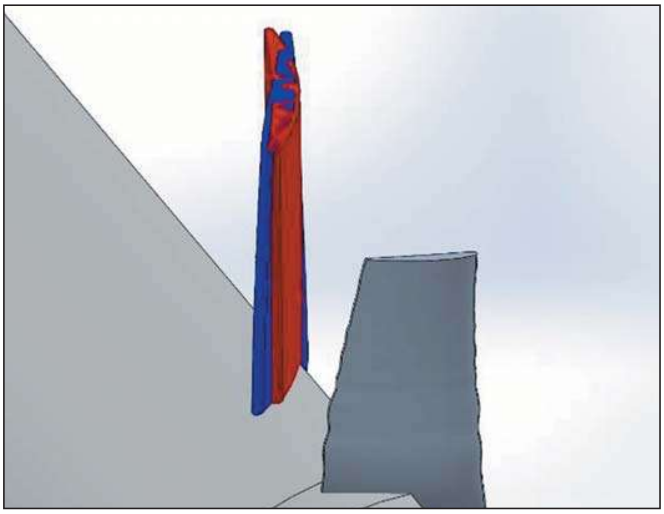

Figure 5. 2D Straight Stator (red) versus 3D Twisted Stator (blue)

but the twist in the 3D stator means that the tip is twisted to match the incidence at design and performs better at higher flow rates than the 2D stator which experiences separation at these higher flow rates.

Figure 6 and Figure 7 show the complete map for both options. The flow over the straight stators breaks down at high

flow rates limiting the useful setting angles on the rotor to below 30° to the nominal whereas the 3D stators continue to provide effective pressure rise at rotor setting angles of 35°. The fan with straight stators achieves an almost identical maximum total efficiency in the region of 5° setting angle and 14m^3/s of around 89% at a single point as that achieved by the 3D stator fan over a wide range of flow rates and setting angles.

The end result is that by moving to the 3D stator set this secondary fan has a high efficiency effective range from 15 to 30m^3/s and 1 to 2.1 kPA and this entire map falls within the power range of motors that can be fitted within the barrel. The 2D stators offer a useful, efficient range of 13 to 17m^3/s and 1-1.8 kPa by comparison but with an average of a 1-3% efficiency deficit.

5. DISCUSSION

It has been shown above that the use of advanced 3D design of the stators alone can yield significant or measurable improvements in efficiency and yield improvements in the physical dimensions of the fans and increase the useable high efficiency area of a given fan's performance for no penalty in input power. In practice this might mean that the fan purchased by the client might retain its efficiency better over its life in the mine as the length of ducting increases, for example.

Sadly, for the environment, however, cost is often the primary driver in industry. With this in mind it is worth viewing these aerodynamic results through a different lens.

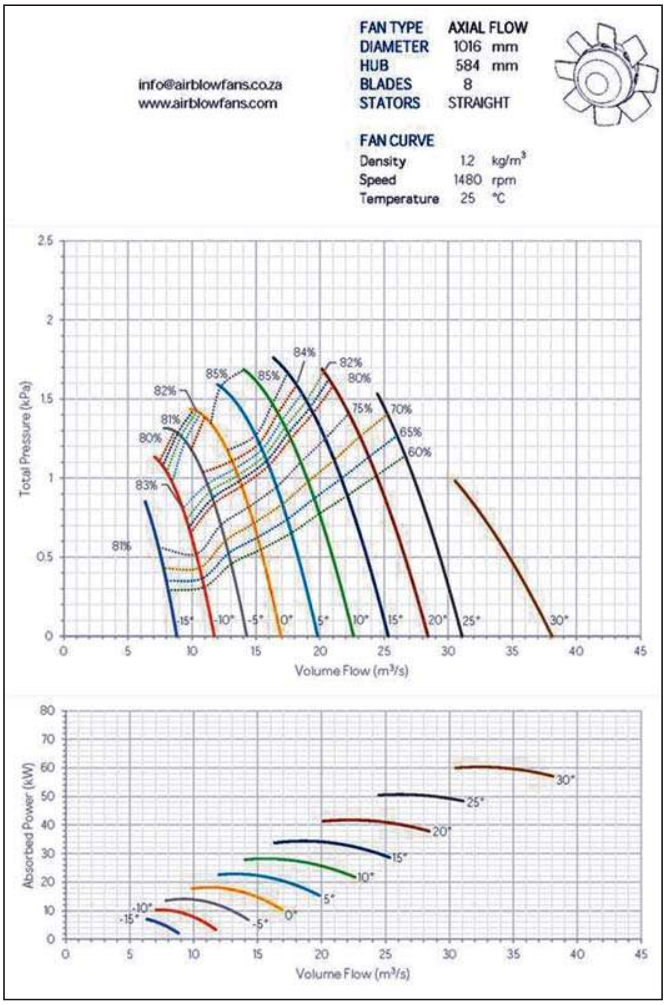

Figure 6. Performance map for 40" Fan with 23" Barrel and 2D Straight Stators

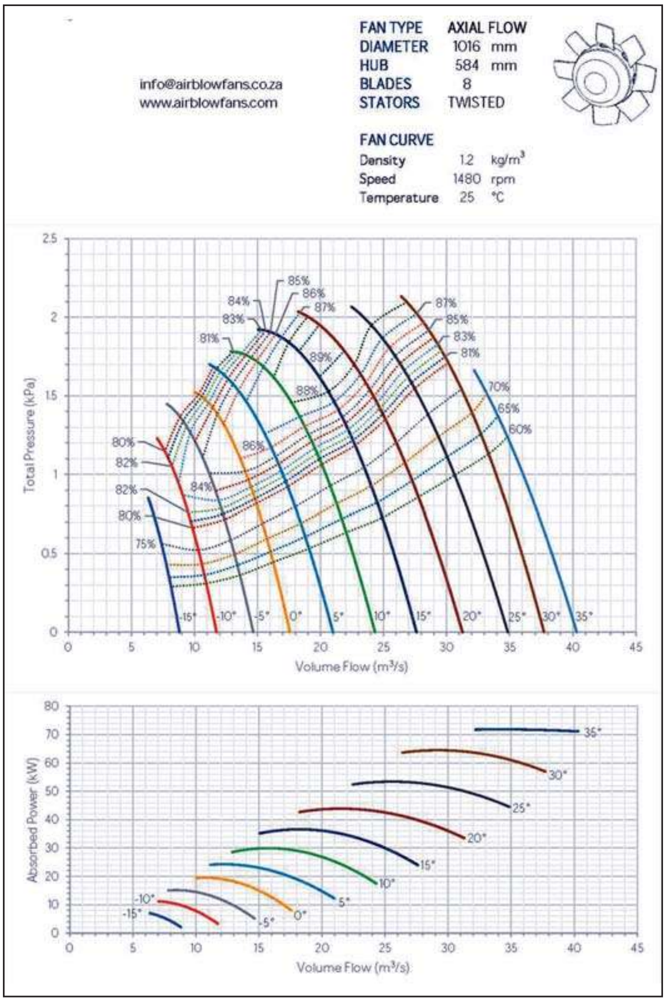

Figure 7. Performance map for 40" Fan with 23" Barrel and 3D Twisted Stator

For the 2m Primary Fan described above the cost of implementing the bowed stators would amount to roughly 6% of the purchase price. At today's electricity tariffs and assuming an average power consumption and a 24 hour up-time with a 5% aerodynamic efficiency improvement translating to a 5% reduction in electricity usage one finds that the additional capital cost would be recovered in less than 3 months of operation.

The same calculation for the cheaper, mass produced 40" secondary is a little more difficult to formulate at the additional tooling required represents as much as 35% of the selling price of a fan.

But if we assume a 3% efficiency improvement and a 24 hour up-time as well as a production run of just 20 fans per tooling set then the additional capital would be paid back in 2 months of operation.

Obviously this is a simplified analysis but the results are quite clear, the additional cost of producing more efficient fans utilizing technology commonplace in aircraft gas turbines can be paid back from operational savings in a small fraction of the expected life of the fan. Beyond the cost advantage lies the direct benefit to the environment, particularly in South Africa with the dominance of coal fired electricity production.

6. CONCLUSION

The application of computational fluid dynamics in combination with advanced techniques derived from aerospace technologies, bowing and twisting the stators of a ventilation fan has been demonstrated to give between 1 and 5% improvements to the aerodynamic efficiency of an already optimized mining ventilation fan and increase the operational range of the fan at that level of efficiency.

Furthermore, the cost of producing these fans with the increased complexity in blading has been calculated to amount to approximately 6% for a primary fan or 3% for a production run of 20 fans in the secondary class.

This additional capital cost can be paid back in reduced operating costs in as little as 2 to 3 months, or well within the expected lifetime of the fan.

7. REFERENCES

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