A Powerful Wind of Change

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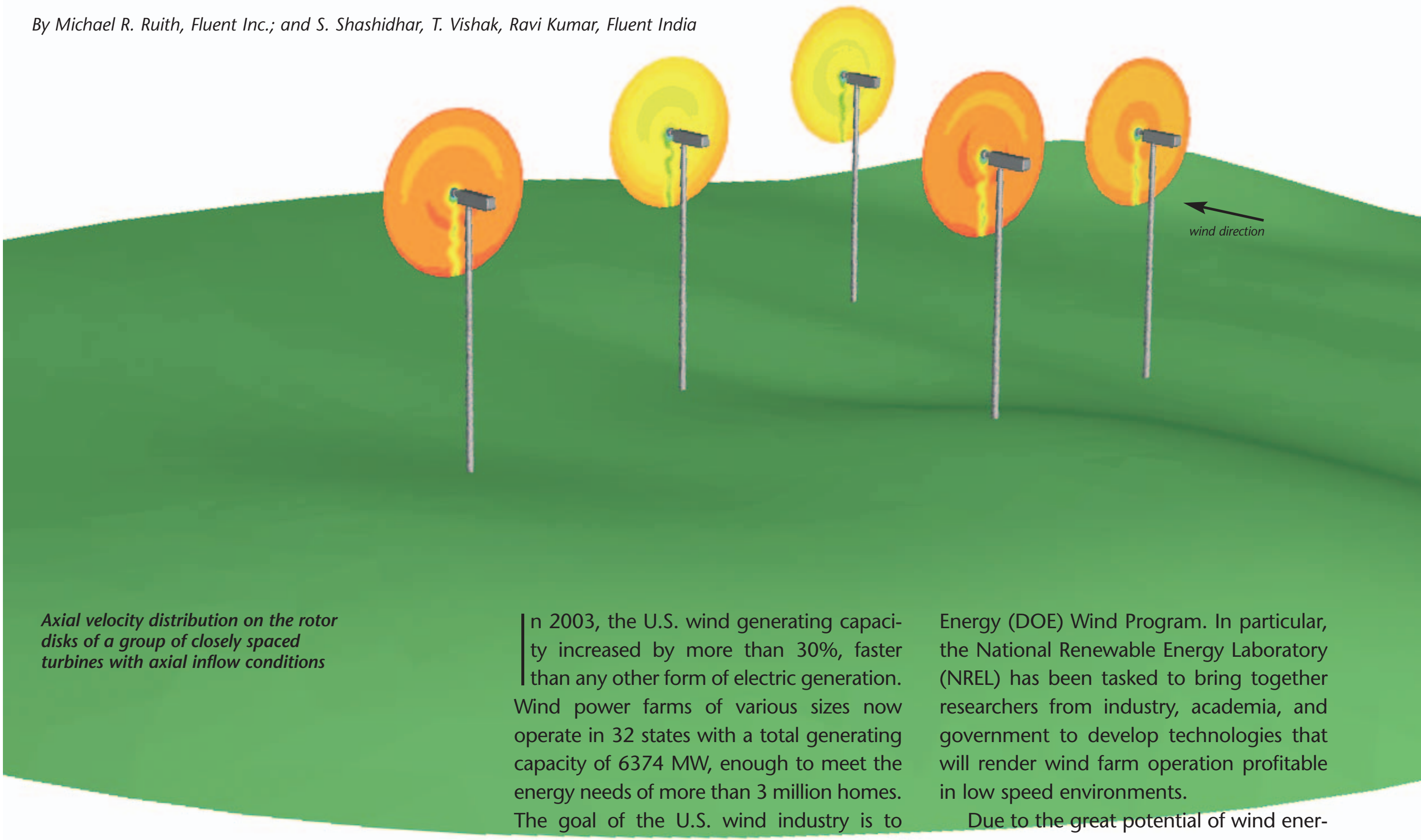
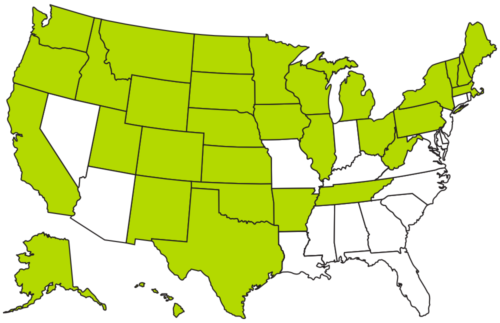


Axial velocity distribution on the rotor disks of a group of closely spaced turbines with axial inflow conditions

In 2003, the U.S. wind generating capacity increased by more than 30%, faster than any other form of electric generation. Wind power farms of various sizes now operate in 32 states with a total generating capacity of 6374 MW, enough to meet the energy needs of more than 3 million homes. The goal of the U.S. wind industry is to increase the installed wind power capacity to about 100 gigawatts (GW) by 2020. This would account for nearly 6% of the estimated total electrical power consumed in the U.S. – a moderate goal, considering that the winds that blow across the Great Plains alone could generate more electricity than the U.S. currently consumes per year [1]. Across the windy Atlantic, the E.U. pursues an even loftier goal – 150 GW or about 12% of the total available power is expected to be harvested from wind farms by 2020 [2].

The wind farms that have been built in the U.S. to date primarily take advantage of the country's best wind resources (Class 6 or 7, with speeds of 8.0 to 11.1 m/s, 50 m above the ground). Class 4 (7.0 to 7.5 m/s) wind resources are much more common, and are often located close to load centers, making them especially attractive to develop. However, their cost in $/kWh has been higher [1]. Development of those geographical areas to ensure continued industry growth is the goal of the Department of Energy (DOE) Wind Program. In particular, the National Renewable Energy Laboratory (NREL) has been tasked to bring together researchers from industry, academia, and government to develop technologies that will render wind farm operation profitable in low speed environments.



2003 U.S. Wind Capacity Map; wind farms of various sizes now operate in 32 states, generating 6374 MW [1]

Due to the great potential of wind energy, more utilities are seriously evaluating its addition to their electric generation portfolios. However, because wind is a variable resource, it raises concerns about how it can be integrated into the grid, particularly with regard to its effect on regulation, load following, scheduling, line voltage, and reserves. A lack of acceptance by the utilities can inhibit the increase of installed wind energy capacity. Thus it is critical to develop simulation tools that enable the analysis of wind farm operations under various wind conditions.

Wind turbines operating in farms experience wake effects. Each wind turbine slows down the wind behind it as it pulls energy out of the wind and converts it to electricity. Ideally, turbines should be spaced as far apart as possible in the prevailing wind direction. Yet land use and the cost of connecting wind turbines to the local grid favor spacing them closer together. Typically, turbines in wind farms are spaced between 5 and 9 rotor diameters apart in the prevailing wind direction, and between 3 and 5 diameters apart in the perpendicular direction. Wake effects for a typical farm layout can therefore be very large during off-design wind conditions. Environmental effects originating from the presence of hills, forests, buildings, power lines, and wind turbine towers also affect the wind flow through the farm and, ultimately, the availability of its power output.

While wind farm modeling is still in its infancy, CFD has been widely adopted to model flow fields around turbine blades with various degrees of accuracy. A new virtual blade model (VBM) has recently been added to FLUENT's turbomachinery modeling capabilities. Initially, the VBM was developed to approximate a helicopter rotor in a time-averaged manner to simulate its effect on the fuselage and other nearby components during hover and forward flight. It replaces the rotor blades with variable momentum sources on an actuator disk, allowing the pressure jump across the disk to vary with radius and azimuth. This eliminates the need to generate individual meshes over each of the rotor blades, so fewer cells are needed, and mesh generation time is reduced. The magnitudes of the momentum sources are obtained from blade element theory (BET), allowing for varying twist, chord and airfoil types along the span. The non-linear aerodynamic interaction between the rotor system and other structural components – and between different rotor systems – is solved by coupling the BET with the governing flow field equations. Airfoil tables required by the BET can be specified as functions of Mach and Reynolds number, allowing both incompressible and compressible flows to be treated accurately. Coning and flapping, as well as collective and cyclic pitch can be taken into account, whereby the blade pitch can be calculated through a trim routine to achieve a specified thrust coefficient and zero moment about the hub. The method has been validated with experimentally measured surface pressures on generic helicopter fuselages [3]. It is currently implemented via user-defined functions (UDFs) in FLUENT and is accessible through the graphical user interface (GUI).

As a test of the VBM for horizontal axis wind turbines (HAWT), a modified Grumman Wind Stream 33 was studied [4, 5]. It consists of a 10m diameter, three-bladed (S809 airfoil, phase II), downwind, free-yaw, stall-controlled turbine, operating at a constant speed of 72 rpm. In addition to the VBM, the turbine was also simulated using a single rotating reference frame (SRF) model. While the SRF model incorporates the full geometry of the turbine blade, all non-axisymmetric stationary components, such as the drive-train and tower, must be ignored. For both numerical approaches, predictions for the power generated as a function of wind speed were found to be in good agreement with experiment [4] and other numerical methods [5].

While FLUENT's VBM and SRF models of a single isolated turbine are similar to traditional numerical approaches, only the VBM can take into account added complexities in a rigorous fashion, while keeping the computational mesh manageable. In another example studied, a wind farm consisting of five modified Grumman Wind Stream 33's, distributed over a hilly terrain was simulated. A cylindrical domain of diameter 160 m (16D) and average height 40 m (4D) required fewer than 2 million cells.

A constant velocity profile was assumed, but a more appropriate logarithmic velocity profile approximating the atmospheric boundary layer [6] can be easily implemented. By examining the velocity in the free stream (axial) direction on the rotor disks, the wake effect of the upstream turbines could be illustrated. For the worst-case wind direction with full overlap between the wake and downstream wind turbine, the downstream turbine's power output is reduced by almost 50%.

These results demonstrate that the VBM is a first and important step towards simulating the effects of wind conditions on the potential power generated by wind farms, forming the basis for their routine and financially profitable operation in the electrical grid by utility companies. ■

references:

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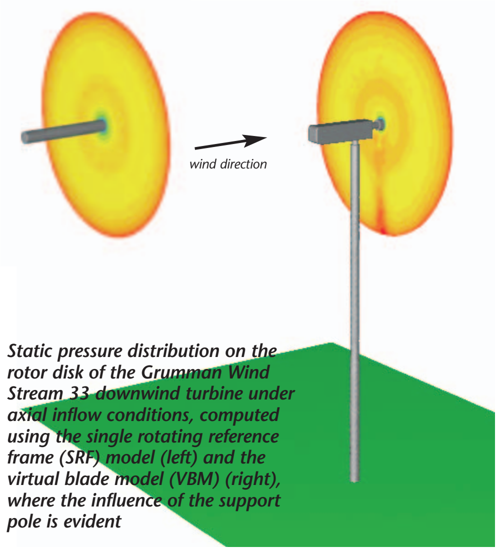
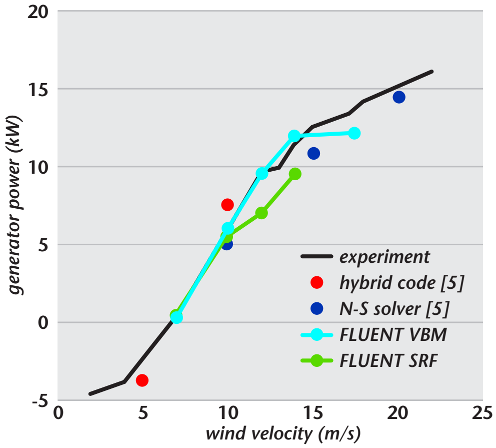
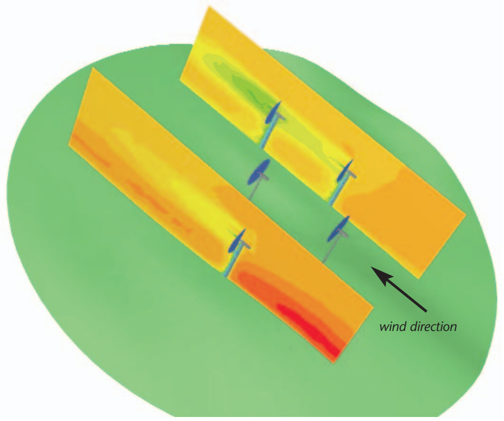


Static pressure distribution on the rotor disk of the Grumman Wind Stream 33 downwind turbine under axial inflow conditions, computed using the single rotating reference frame (SRF) model (left) and the virtual blade model (VBM) (right), where the influence of the support pole is evident



Comparison of the power generated by various models for the test rotor.



Axial velocity distribution on planes passing through closely spaced turbines reveals the strong wake effect on the downstream wind turbine under this worst-case wind direction