The Department of Mechanical Engineering

Michigan State University

Ph.D Dissertation Defense

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ABSTRACT

AERODYNAMIC DESIGN AND CHARACTERIZATION OF NOVEL WOUND COMPOSITE MULTISTAGE COUNTER-ROTATING AXIAL COMPRESSIONS

By

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This thesis examines two different generations of axial compressor developed within the framework of the patented wound composite impeller technology created at Michigan State University. The technology itself allows for a departure from both the construction and
operation of traditional single and multistage axial machines. Rather than using casting and machining methods to produce the impellers, they are wound from carbon fiber or other fiber/matrix material on a mandrel with curved slots. Winding layer-by-layer in the axial direction builds the blades while simultaneously creating the outer (and inner) shroud(s). The winding technique ensures that the fibers are closely aligned with the forces associated with high speed rotation, thereby yielding a high strength, light weight composite rotor capable of operating in chemically aggressive environments once cured. Traditional multistage axial compressors typically have a single drive shaft and hence require unidirectional rotation at a single operating speed. Non-rotating stators are utilized between rotors to impose the appropriate velocity distribution at the subsequent rotor inlet. The stators however do not perform useful work in terms of boosting the total pressure, and they contribute substantially to the overall footprint of a multistage machine. The employment of counter-rotating stages serves to eliminate the need for all intermediate stators as they themselves impose the necessary velocity distribution for the subsequent rotor while simultaneously performing useful work. Counter-rotation can be achieved by integrating a permanent magnet motor with each rotor. Rotors can be mounted on a non-rotating shaft and can therefore be driven in opposite directions through the use of variable frequency drives.

Initially developed for strength and ease of construction, a full geometric characterization of the first-generation “star pattern” impeller is performed and it is found that it operates under the forced-vortex flow regime. Reductions in terms of polytropic efficiency, mass flow rate, and total pressure ratio are seen from analytical prediction to numerical simulation, and again from simulation to experimental measurement. These reductions have led to the development of the second-generation impeller, which operates under the free-vortex flow regime.
Enhanced performance of single stage second-generation impellers in numerical simulation has led to a vast investigation matching geometrical parameters, rotational speeds, and flow velocities to best-point operating conditions for up to seven counter-rotating stages compressing initially saturated water vapor under vacuum pressure for 22 different inlet temperatures. Numerical simulations of select cases agree well with analytical predictions.

For achieving maximum specific work transfer from the rotors to the working fluid, it is determined that the critical relative Mach number at each rotor tip should always be maximized. Hub/tip ratio at the first rotor inlet, aspect ratio, critical absolute Mach number, and turning angle are all temperature-dependent. The number of stages employed also has a large effect on how each rotor behaves (e.g. the second stage of a three stage machine looks and behaves differently from the second stage in a six stage machine), however utilizing an odd vs. an even number of total stages will have a much larger effect on inlet flow angle and the dimensionless flow coefficient, blade loading coefficient, and specific speed of each rotor.

Seven other gas mixtures have been investigated in similar fashion and exhibit similar behavior. Overall, billions of designs have been evaluated and the best operating conditions are determined for each individual set of inlet conditions and number of stages used. This research lays the necessary ground work for multistage counter-rotating axial compressor construction.