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A novel twin-rotor radial-inflow air turbine for oscillating-water-column wave energy converters

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ABSTRACT

A novel air turbine for bidirectional flows in oscillating-water-column wave energy converters is presented and its performance is analyzed. The turbine is based on a pair of conventional radial-inflow rotors mounted on the same shaft, complemented by the corresponding guide vane rows, by a curved-duct manifold arranged circumferentially in a period manner and by a two-position cylindrical valve. Numerical values of the performance of the whole machine were obtained from published experimental data of the flow through a conventional radial-inflow gas turbine, together with CFD (computational fluid dynamics) results for aerodynamic losses in the curved duct manifold. Four different geometries, combined with five different sizes, of the curved-duct manifold were numerically simulated. Windage losses, that occur at the inactive rotor and are inherent to the machine conception, were found to be a major loss. A peak value of about 86% was obtained for the overall efficiency of the machine. Comparisons are presented between the new turbine and the biradial turbine (sliding guide-vanes version), the latter being possibly the most efficient self-rectifying turbine model-tested so far. The new turbine was found to be more efficient, both in peak instantaneous efficiency and in maximum average efficiency in random waves, by a margin of about 8%.

1. Introduction

The OWC (oscillating water column) device with air turbine is arguably the simplest type of wave energy converter and, possibly more than any other, has been object of extensive development effort. It has a wide range of applications: isolated, integrated into breakwaters, and in a variety of floating configurations. The success of the OWC depends largely on the performance and reliability of the air turbine. The use of self-rectifying turbines has the advantage of not requiring a rectifying valve system. Several types of self-rectifying turbines have been proposed and developed, and in some cases equipped prototypes tested under real sea conditions. Most self-rectifying air turbines for wave energy conversion proposed and tested so far are axial-flow machines of two basic types: the Wells turbine and the impulse turbine. An extensive and detailed review of Wells turbines was published in Ref. [1]. For the impulse turbine see Ref. [2]. More recent reviews of self-rectifying air turbines for OWCs can be found in Refs. [3–7].

Several variants of the Wells turbine have been developed: without or with guide vanes, counter-rotating, bi-plane, multi-stage (see Ref. [5]). Peak efficiencies up to about 75% were found to be attainable in model testing of Wells turbines with sufficiently large models and Reynolds numbers. Regardless of the type of Wells turbine, the curve of efficiency versus pressure head is characterized by a (more or less) sharp fall that occurs when the angle of incidence at the rotor blades exceeds the stall-free limit. The aerodynamic losses due to rotor blade stalling in practice severely limit the range of operation of the Wells turbine and are its main drawback. Because of its own conception, the rotational speed (or more precisely the rotor blade tip speed) of the Wells turbine is much higher as compared with self-rectifying impulse turbines in identical application. This may lead to limitations, due to the need

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to avoid shock waves or excessive centrifugal stresses, which is a constraint in the more energetic wave climates, or in OWCs designs characterized by large pressure heads like the spar-buoy OWC; in such cases, mechanically more complex multi-stage Wells turbines may be required as alternatives to impulse turbines [8].

The efficiency of the self-rectifying axial-flow impulse turbine with fixed guide vanes is severely affected by the losses at the entry to the downstream row of guide vanes. Peak efficiencies measured in model testing do not exceed about 50% (as compared with about 75% for the most efficient Wells turbines). On the other hand, the efficiency curves do not exhibit the sharp drop typical of most Wells turbines. The performance of the axial-flow impulse turbine can improve by about 10–15% if pivoting guide vanes are used instead of fixed ones. However, the mechanical complexity of this solution has deterred its use. A way to reduce the aerodynamic losses at the second row of guide vanes is to offset the guide vanes radially and axially from the rotor in order to reduce the kinetic energy (and so the losses due to stalling). This has been done in the HydroAir turbine that equipped the Oceanlinx Mk3 multi-chamber floating OWC prototype [7].

The so-called biradial turbine [9,10], Fig. 1, is an impulse turbine that is symmetrical with respect to a plane perpendicular to its axis of rotation. The flow into, and out of, the rotor is radial. The rotor is surrounded by a pair of radial-flow guide-vane rows, each row being connected to the corresponding rotor inlet/outlet by a duct whose walls are flat discs. In one of the versions of the biradial turbine, the guide vane rows may be removed from, or inserted into, the flow space by axially displacing the whole guide vane set, so that the downstream guide vanes are prevented from obstructing the flow coming out of the rotor. In this version, the radial distance between the rotor and the guide vanes is small, see Fig. 1. The measured peak efficiency of a turbine model was about 79%, possibly the highest efficiency of a self-rectifying air turbine measured so far.

If, in a single-stage conventional turbine, with a row of guide vanes followed by a bladed rotor, the sign of the pressure head is changed (and the rotational speed is kept unaltered), the flow rate (apart from changing sign) becomes substantially smaller (and the turbine performance becomes very poor). This has led to the idea of associating two identical “conventional” air turbines (turbines T1 and T2) in parallel to convert the pneumatic energy from an OWC, such that, for a given pressure head situation, the flow sequence guide-vanes-rotor-blades in turbine T1 is reversed with respect to turbine T2 (see Refs. [11,12]). This topology is shown in Fig. 2, where the twin turbines are of axial-flow type. With this arrangement, for a given pressure head (independently of its sign), most of the flow is admitted to one of the turbines (that is driven with good efficiency) while a smaller fraction of the flow is admitted to the other turbine (that is in reverse mode and operates at very low efficiency). The two turbines can be coupled to a common electrical generator (as in Fig. 2) or, alternately, each turbine is coupled to its own generator. Since the turbines are not symmetrical, their rotor blades need no longer to be symmetrical with respect to the mid-chord point, as appears to be the case in Fig. 2. Some positive degree of reaction may be convenient. Model testing of a unidirectional-turbine pair in a rig capable of bi-directional oscillating air flow is reported in Ref. [12]. The turbine rotor diameter was 165 mm and each turbine was coupled to its own generator. A peak efficiency of 0.6 was measured. The aerodynamic performance of the twin unidirectional turbine configuration was numerically simulated in detail in Ref. [13]. It was found that the flow rate through the turbine in reverse mode is about one-third of the total flow and produces a negative torque which reduces the system efficiency if the two turbines are directly connected to the same electrical generator.

Descriptions of other types of air turbines for bidirectional flows can be found in Refs. [5,7].

The paper proposes a new patented self-rectifying air turbine [14]. The turbine is characterized by a twin rotor, i.e. two rows of rotating blades axially offset from each other, mounted on the same shaft, complemented by corresponding guide vanes, as in a conventional axial-flow or radial-flow turbine. The reciprocating air flow between the OWC chamber and the atmosphere takes place as unidirectional flow alternately through one or the other bladed set. This is made possible by a double set of curved ducts arranged circumferentially in a period manner, and by a two-position axially-

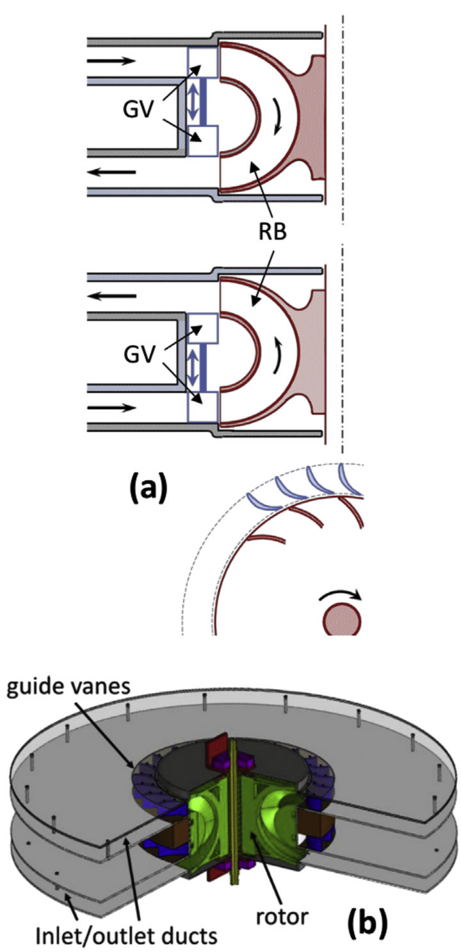

Fig. 1. Biradial turbine: (a) cross sections; (b) perspective view. GV = guide vanes; RB = rotor blades.

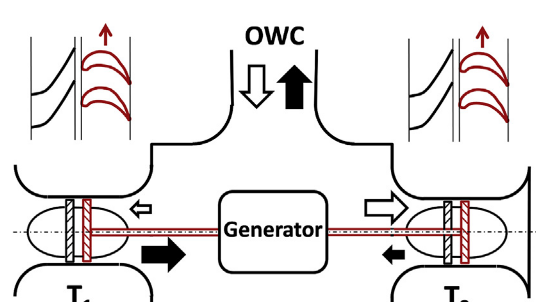

Fig. 2. Twin unidirectional impulse turbine topology [7].