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Coupling of an offshore wind-driven deep sea water pump to an air cycle machine for large-scale cooling applications

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A B S T R A C T

A system for using offshore wind energy to directly provide large-scale cooling through the exploitation of cold deep seawater below thermocline formations is proposed. The concept is based on an offshore wind-driven hydraulic pump supplying high pressure deep seawater to a land based plant. This pressurised seawater is used to power a hydraulic turbine which drives an inverse Brayton air cycle machine, and is then diverted to a heat exchanger to cool the pressurised air prior to flowing back to the sea.

A mathematical model for steady-state performance analysis of the proposed system under specified ambient conditions is presented. It was found that the system coefficient of performance was highest at low wind speeds and improved with increasing ambient temperature and humidity. This makes the system ideal for hot and humid climates. The availability of a sufficiently cold deep seawater resource was also found to be crucial for the viability of the system.

1. Introduction

The existing offshore wind systems are mainly based on onshore technology with slight modifications to cater for offshore conditions. Such technology leads to a cost gap between offshore wind and other renewable power generation, and this may hinder the viability of offshore wind energy projects [1]. The main driver for the offshore wind industry is cost reduction, which can be achieved by developing new technologies catering for the specific demands of the offshore environment [2].

An innovative offshore-specific wind turbine concept is the Delft Offshore Turbine (DOT) [3–5], which aims to reduce the complexity of offshore wind energy technology by shifting to hydraulic transmission and centralised electrical generation. In this concept, the turbine rotor is connected to a radial piston pump which delivers the power to a hydraulic motor at the turbine base through a closed-loop oil circuit. The hydraulic motor drives a variable displacement pump which delivers pressurised seawater to a centralised hydroelectric plant [4].

Improved standards of living are increasing the energy demand to cool buildings for thermal comfort annually. The demand in Europe is expected to increase threefold by 2020 compared to the years 2006 and 2007 [6]. Climate change is also expected to contribute to this demand increase. To date, the majority of the cooling is achieved by processes relying on electricity, leading to higher electricity demands during the summer period.

Air-cooled vapour-compression chillers, which are widely used in small to medium buildings, operate with a condensing temperature of 15–20 °C above outdoor air temperature. This high condenser temperature leads to low COP values in the range of 2.6–2.9 [7,8]. To improve the COP, a lower and more stable temperature heat sink, such as water, is preferred. The supply of constant low temperature water to the condenser is typically obtained using either cooling towers [9,10], ground source cooling [11,12], or natural water bodies such as lakes and seawater [13,14]. Using such heat sink, the overall COP of the system reaches values in the range of 4.7–5.2 [8].

The main objective of this work is to combine the innovative concept of an offshore hydraulic wind turbine with large-scale cooling applications. Such hybrid system could potentially result in a more economically viable solution while providing superior performance in transient and fluctuating wind conditions.

This paper is organised as follows. Firstly, a discussion on seawater source cooling and air cycle machines is presented, together with an overview of the relevant research which has been published prior to the compilation of this work. This is followed by

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Nomenclature

A	area
C_c	contraction coefficient
C_v	Pelton wheel nozzle velocity coefficient
COP	coefficient of performance
D	diffusion factor
M	mach number
N	rotational speed
Nu	Nusselt number
N_r	number of tube rows/passes
P	power
Pr	Prantl number
P_f	Fin Pitch
P_l	Longitudinal Pitch
P_t	Transverse Pitch
Q	flow rate
R	gas constant
Re	Reynolds number
T	temperature
V	velocity
V_∞	wind speed
Y_t	total pressure loss coefficient
Y^*	normalized total pressure loss coefficient
c_p	specific heat capacity
d_i	tube inside diameter
d_o	tube outside diameter
f	friction factor
h	specific enthalpy
i	incidence angle
i^*	normalized incidence angle
$\dot{m}$	mass flow rate
p	pressure
p_{nozzle}	Pelton wheel nozzle pressure
p_{pump}	hydraulic pump operating pressure
r_h	hub radius
r_m	mean radius
r_t	tip radius
Π	total pressure ratio
ϕ	flow coefficient
ϕ^*	normalized flow coefficient
Ψ	stage loading coefficient
Ψ^*	normalized stage loading coefficient
Ω	rotational speed
α	absolute flow angle
γ	heat capacity ratio
ε	surface roughness
η_p	polytropic efficiency
ρ	density
σ	solidity
τ	total temperature ratio
ψ	pressure coefficient
ψ^*	normalized pressure coefficient

Subscripts

R	relative
a	dry air
sw	seawater
t	total/stagnation properties

a description of the proposed system and a review of the underlying theory used to develop the steady-state model of such system. The computational approach used to solve the mathematical model of the hybrid system is then outlined. Lastly, an overview of the main performance results obtained from the developed model is provided, followed by the main conclusion of the research.

2. Background

As a result of the phenomena of thermal stratification, the temperature of deep seawater tends to be independent of season [15], as shown in Fig. 1. This immense source of renewable thermal energy can therefore be used for cooling applications. If the available water is sufficiently cold, cooling could be provided directly without the use of chillers. Such system, referred to as Deep Sea Water Cooling (DSWC) or Sea Water Air Conditioning (SWAC), can reduce the electrical consumption by 80–90 percent when compared to conventional air conditioning systems [14].

2.1. The OWTEP concept

Existing DSWC systems use electrically-driven pumps to draw

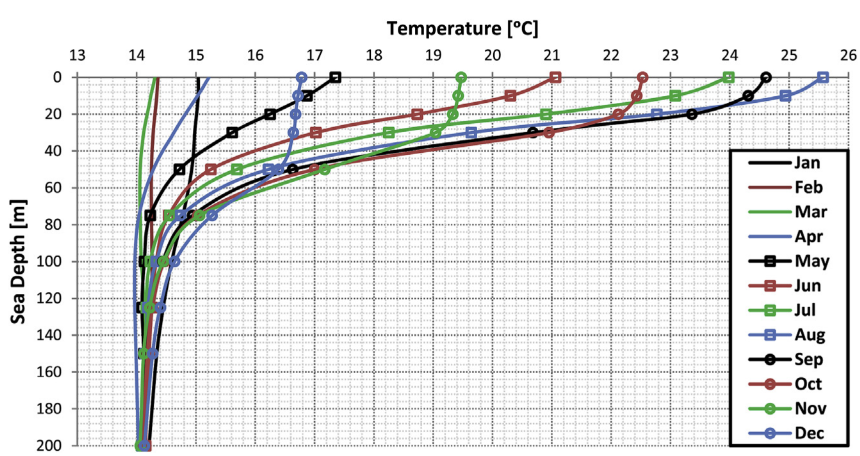

Fig. 1. Monthly temperature-depth profiles for a central Mediterranean location [15].