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Thermoeconomic analysis of shrouded wind turbines

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ABSTRACT

In this study, thermoeconomic analysis of shrouded wind turbines is conduced incorporating different area ratios of the shroud. Key thermoeconomic parameters are examined which include, cost of the power produced, cost of the exergy lost, exergy efficiency, exergetic improvement potential, air mass flow rate through the wind turbine, and power produced. It was concluded that the wind turbine performance improved as the shroud area ratio increased. Consequently, the cost of the power produced became low for the case of high area ratio and vice-versa. It was demonstrated that the cost was significantly high under low wind speed. The same finding was observed for the cost rate of the exergy loss in which the cost was the lowest for the highest area ratio value considered in the present study. The findings also showed that the exergetic improvement potential increased as the wind speed increased and exergetic improvement potential enhanced further at high shroud area ratio.

1. Introduction

Wind turbines are a promising source of renewable energy in which the energy production is in the night and day times. Shrouded or ducted wind turbines are one type of wind turbines that have received some attentions by the researchers and a number of studies had discussed shrouded wind turbines fundamentals [1–5]. Overall, the shrouded wind turbines are characterized by a higher mass flow rate of air passes through the turbine blades as compared to bare wind turbines. Recently, Werle and Presz [6] had analyzed shrouded wind turbines using momentum and energy equations and identified appropriately an axial force coefficient that identifies the performance of the shrouded wind turbines. Their approach has been used in this study as discussed later.

On the other hand, a number of studies had been conducted to analyze the exergetic performance of bare horizontal wind turbines [7–11]. Ozgener [7] assessed the performance of a small wind turbine windmill system. He demonstrated that the energy and exergy efficiencies of NACA 63-622 were higher than that of NACA 4415. Ozgener and Ozgener [8] extended the aforementioned study and examined the exergy performance and reliability of the small wind turbine windmill system. They found that the range of the exergy efficiency was very wide. It was zero at around 2 m/s wind speed and 84% at 12 m/s. In another study, Pope et al. [9] compared the energy and exergy efficiencies of horizontal and vertical axis wind turbines. Redha et al. [10] studied the energetic and exergetic performance considering the weather conditions of Sharjah, UAE. In a different study, Baskut et al. [11] conducted exergy analysis of wind turbine power plants located in Izmir, Turkey. They assumed constant reference temperature and pressure and calculated, for example, the physical exergy upstream of the wind turbines. However, for such a case, the physical exergy of the system was always zero because the reference temperature and pressure were changing with the environment condition and they should not be kept constant in the analysis.

Few studies had conducted thermoeconomic analysis of bare horizontal wind turbines [12–14]. Mostafaeipour [12] statistically analyzed the economics of locating wind turbines in Kerman. Ozgener et al. [13] studied the exergy-economic of a 1.5 kW small wind turbine. They concluded that the rate of exergy loss to the capital cost increased as the wind speed increased and it was between 0.006 and 0.411 for the wind speed range examined. Moreover, Baskut and Ozgener [14] studied the effect of the wind speed variation on the ratio of the exergy loss rate to the capital cost and found that the variation of the ratio was in between 0.125 and 0.587.

It can be observed from the literature review that the exergy and economic studies that had been conducted analyzed bare horizontal wind turbines but no study has been conducted considering thermoeconomic analysis of shrouded horizontal wind turbines. Therefore, the present study is carried out to full fill this gap. In this

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Nomenclature

A	area, m^2
A_E	shroud exit area, m^2
A_t	shroud throat area, m^2
A_r	area ratio
c	cost per unit exergy, $/kW h
$\dot{C}$	cost rate, $/h
CF	capacity factor
CRF	capital recovery factor
$C_{c,t}$	capital cost of the turbine, $
$C_{om,f}$	fixed cost of operating and maintenance, $
$C_{om,v}$	variable cost of operating and maintenance, $
C_s	axial force coefficient
C_p	power coefficient
C_T	actuator disk coefficient
F_s	shroud force, N
i_{eff}	effect rate of return
IP	exergetic improvement potential, W
LEC	levelized energy cost rate, $/h
n	number of years of operation
P	pressure, Pa
$\dot{Q}_{loss}$	heat loss rate, W
r_n	escalation rate
T_P	actuator disk force, N
T_T	turbine work, N
V	wind speed, m^2/s
$\dot{X}$	exergy rate, W
$\dot{Z}$	levelized cost rate, $/h

Greek letters

η_{ex}	exergy efficiency
ρ	density, kg/m^3

Subscripts

1	directly upstream of the turbine blade
2	directly downstream of the turbine blade
e	exit
i	inlet
j	state location
t	turbine

study, we carry out the thermoeconomic analysis of shrouded wind turbines incorporating different shroud area ratios. Firstly, the momentum and energy modeling of a shrouded wind turbine is presented and then thermoeconomic of the shrouded wind turbine is analyzed. A number of parameters are examined, such as exergy efficiency, exergetic improvement potential, cost rate of the power produced, and cost rate of exergy loss.

2. Mathematical modeling

Mathematical analysis of the shrouded wind turbine includes firstly momentum and energy modeling, and then follows exergy and thermoeconomic modeling.

Modeling of the fluid dynamic of bare wind turbines is discussed extensively in the literature. On the other hand, fewer studies have discussed modeling of the shrouded wind turbine as indicated in the introduction section. The fluid momentum modeling herein is based on the approach recommended by Werle and Presz [6]. The main advantages of this approach is due to that the model is simple and used a unified momentum model that can be applied to both bare and shrouded wind turbines. Secondly, the model demonstrates generalize approach of Betz limit that can be applied to both bare and shrouded wind turbines. Thirdly, the model identifies a single critical shroud aerodynamic parameter, which can be used to controls the power extraction level.

Applying momentum balance for the shrouded turbine shown in Fig. 1, one can obtain

$$A_t[P_2 - P_1] + F_s = \rho A_t V_t [V_e - V_i] \tag{1}$$

where A_t is the turbine area, P_1 is the pressure just at the upstream of the turbine and P_2 is the pressure just at the downstream of the turbine (both pressures are within the shroud), ρ is the density, V is the velocity, and F_s is the shroud force. The subscript t refers to the turbine and the subscript i is refer to the far upstream inlet and e corresponds to the far downstream exit, as shown in Fig. 1.

To obtain the power produced by the wind turbine apply energy equation to obtain

$$\dot{W} = 1/2\rho A_t V_t [V_i^2 - V_e^2] \tag{2}$$

Assuming wind turbine operates in the steady state, using Bernoulli's equation, Eq. (2) can be re-written as

$$\dot{W} = A_t V_t (P_i - P_e) \tag{3}$$

However, based on the Kutta–Joukowski theorem, the shroud force, F_s, is proportional to the force induced by the pressure variation across the turbine blades. Therefore, the axial force coefficient can be defined as [6]

$$C_s \equiv F_s / A_t [P_2 - P_1] \tag{4}$$

Apply Bernoulli's equation to the above equations, one can obtain

$$F_s = 1/2\rho A_t [V_e^2 - V_i^2] C_s \tag{5}$$

Using the above equations, the velocity of the flow in the shroud can be defined as

$$V_t = 1/2 \cdot [1 + C_s][V_i + V_e] \tag{6}$$

Similarly, the thrust produced from the turbine can be written as

$$T_T = A_t [P_2 - P_1] + F_s \tag{7}$$

To obtain the power coefficient, C_p, apply the above equations which results in

$$C_P = 1/2[1 + C_s] C_T [1 + \sqrt{1 - C_T}] \tag{8}$$

where C_T is the actuator disk coefficient and it is defined as

$$C_T = \frac{T_P}{1/2\rho A_t V_i^2} \tag{9}$$

where T_p is defined as

$$T_P = A_t \cdot \Delta P \tag{10}$$

where ΔP is the change in the turbine pressure. The area ratio of the shroud is defined as the area of the shroud outlet to the area of the shroud throat, which can be written as

$$A_r = A_E / A_t \tag{11}$$

On the other hand, the exergy balance equation can be defined as

$$\dot{X}_{in} - \dot{X}_{out} - \dot{X}_{dest} = \dot{X}_{st} \tag{12}$$

where $\dot{X}$ is the exergy rate. The subscripts *in*, *out*, *dest*, and *st* refer to inlet, outlet, destroyed, and stored, respectively. Notice that the