Energy Conversion and Management 87 (2014) 145–155

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

The experimental study on the wind turbine's guide-vanes and diffuser of an exhaust air energy recovery system integrated with the cooling tower

W.T. Chong [a,*], W.P. Hew [b], S.Y. Yip [b], A. Fazlizan [a,b], S.C. Poh [a], C.J. Tan [a], H.C. Ong [a]

[a] Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
[b] UMPEDAC, Level 4, Wisma R&D, University of Malaya, Jalan Pantai Baharu, 59990 Kuala Lumpur, Malaysia

ARTICLE INFO

Article history:
Received 23 December 2013
Accepted 1 July 2014
Available online 26 July 2014

Keywords:
Cooling tower
Energy recovery
De-carbonization
Wind turbine
On-site energy generation
Renewable energy

ABSTRACT

An assembly of two vertical axis wind turbines (VAWTs) and an enclosure is installed above a cooling tower to harness the discharged wind for electricity generation. The enclosure consists of guide-vanes and diffuser-plates, is used to enhance the rotational speed of the turbines for power augmentation. The angle of the guide-vanes is optimized to ensure the oncoming wind stream impinges the rotor blades of the turbine at an optimum angle. The diffuser-plates are tilted at an optimum angle to increase the discharged airflow rate. The performance of the system is tested in the laboratory followed by a field test on an actual size cooling tower. The VAWT performance is increased in the range of 7–8% with the integration of enclosure. There is no significant difference in the current consumption of the fan motor between the bare cooling tower and the one with installed VAWTs. With the presence of this system, approximately 17.5 GW h/year is expected to be recovered from 3000 units of cooling towers at commercial areas, assuming the cooling tower is driven by a 7.5 kW fan motor and operates 16 h/day. This amount of recovered energy can also be translated into 13% reduction in CO_2 emission.

1. Introduction

World energy demand has shown a remarkable increase over the past century due to population growth and economic development. Currently, there are 7.1 billion people in the world [1]. In 2008, world primary energy consumption from all sources was recorded at 514 EJ (EJ is exajoule = 10^{18} J) and 80% of it was generated from fossil fuels. It is projected to increase to 1000 EJ or more by the year 2050 [2]. Due to the uncontrolled population growth, the increase in fossil fuel consumption for energy generation is inevitable. However, the overconsumption of fossil fuel brings harmful impacts on the world's climate due to greenhouse gas (GHG) emissions. GHGs are the main contributor to anthropogenic climate change and it poses significant risks for human health, welfare and natural ecosystems. Two thirds of the anthropogenic GHGs emission is accounted by the energy related emission since all energy systems emit GHGs [3]. Taseska et al. have reported that the GHGs emission associated with energy demand is tabulated with the value of 6406 kilotonnes CO_2 equivalent in the year 2025 (which is an additional compared to year 2008) [3].

In order to reduce the dependence on fossil fuels for energy generation, renewable energy (RE) plays a critical role in reducing the GHGs emission leading the world toward fossil fuel independence. RE is important for sustainable development since it is natural, replenishable and has great potential for cost reduction, as opposed to the rise in fossil fuel prices. Recently, intensive researches have been done on improving the efficiency of the RE resources with the aim of converting the present energy systems into 100% RE electricity systems. Wind energy is the second biggest source of RE after solar energy. It is the fastest growing RE source in the world with an annual growth rate of 30% [4]. The share of wind energy is 14% at the global scale on the total mid-term RE resources potential and this value reflects its maturity in technology [5]. However, the uncertainty in wind energy is the main problem in matching the increasing demand for RE. The operation of wind power is susceptible to changing wind patterns resulting from climate change [6]. Thus, an efficient method is strongly demanded to harness the uncertain wind energy.

2. Concerns for installation of an on-site energy generation system

On-site renewable energy generation is useful for sustainable electrical power generation leading toward CO_2 abatement [7].

* Corresponding author. Tel.: +60 12 7235038; fax: +60 3 79675317.
E-mail addresses: chong_wentong@um.edu.my, chong_wentong@yahoo.com (W.T. Chong).

http://dx.doi.org/10.1016/j.enconman.2014.07.009
0196-8904/

However, various problems have to be considered when adopting the system close to the energy demand area including the land area [8], the safety and the variation in RE resources. Green space coverage for the on-site RE generation is declining and becoming more limited with the increase in urban density and an unprecedented world population growth [9]. Many research works had been done on enhancing the efficiency and increasing the total amount of generated energy using a localized RE generation system built in a limited area. Shrouded diffuser had been employed to improve output power of a wind turbine. Ohya et al. has reported that the power coefficient of a diffuser shrouded wind turbine is 4 times higher than the bare wind turbine [10]. The power generated from the oncoming wind is maximized using a power regulation control system embedded in the wind turbine generator [11]. With regards to the safety and reliability of the system, the author had developed a 3-in-1 wind-solar hybrid renewable energy and rainwater harvester for urban high rise application with a vertical axis wind turbine enclosed within a power-augmented-guide-vane (PAGV). Estimated annual energy savings of about 160 MW h/year is expected from this system due to the improved approaching wind stream to the Sistan turbine (15 m × 6 m) caused by the PAGV (30 m × 12 m) [12]. From the CFD flow visualization, higher mass flow is transported and channeled to rotor blades which contributed to higher output power (5.8 times higher) [13]. The variation of the RE resources, i.e. the insufficient natural wind speed for power generation is another problem faced by the system. In Malaysia, the wind speed profile is generally low and it fluctuates throughout the year ($V_\infty < 4$ m/s for more than 90% of total wind hours with its maximum only 5.4 m/s at 10 m altitude) [14–16]. Thus, it is not realistic to harness the natural wind in Malaysia.

In this paper, an exhaust air energy recovery system is developed to extract energy from unnatural wind resources, e.g. the discharged air from a cooling tower for electricity generation. In a cooling tower, the heat from a process is carried by the air then dissipated to the environment in high speed through the discharge outlet. This proposed system is used to capture part of kinetic energy that discharge from the tower. It consists of two vertical axis wind turbines (VAWTs), 4 guide-vanes and 2 diffuser-plates are installed at the outlet of a cooling tower. In the laboratory test, the effects of the guide-vanes and the diffuser-plate on the rotational speed of the turbines were investigated. The angle of the guide-vanes was optimized to increase the rotational speed of the turbines. In the field test, the wind speed distribution along the radius of exhaust air fan outlet was determined. The positive torque region of the turbine was placed at the position having the highest wind speed for power augmentation. The influence of the system on the power consumption of the cooling tower was investigated. The equivalent amount of CO_2 emission was calculated from the total amount of energy recovered from this system.

3. Working principle of an on-site exhaust air energy recovery system

3.1. General set-up and working mechanism of the designed system

The general set-up of the innovative exhaust air energy recovery system is depicted in Fig. 1. It is comprised of 2 vertical axis wind turbines (VAWTs) mounted in cross-wind orientation on the top of an induced draft counter flow cooling tower's outlet to tap the discharged air for electricity generation. Cooling tower is a heat removal device that transfer heat from a process system through evaporation process whereby some of the water is evaporated into the moving air stream drawn by the cooling tower. Subsequently, the air dissipated to the environment at the discharged outlet drafted by the fan. According to Hensley [17] in his book

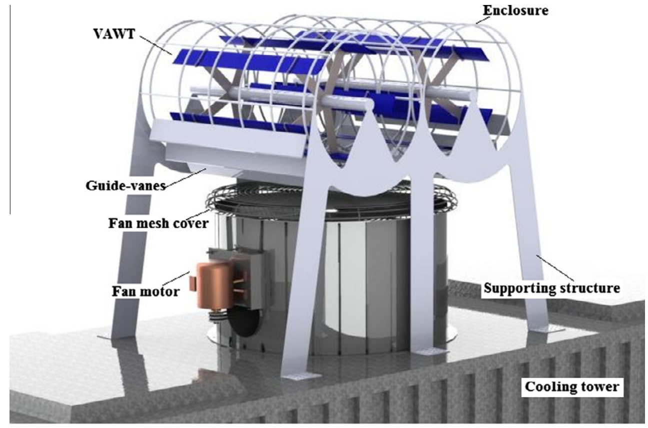

Fig. 1. General set-up of the exhaust air energy recovery system above a cooling tower.

(Cooling Tower Fundamental), the normal discharged velocity from an induced draft tower is about 9 m/s [17]. Each cooling tower possesses a designed mass ratio of water flowing through the tower to the air flow according to the cooling tower heat load and size for best cooling tower effectiveness [18]. On the top of that, discharged air from the cooling tower is necessary to reject high enough to the atmosphere and thus, one of the problems encounter by cooling tower industries, i.e. re-entrainment of discharged air back to the same or adjacent unit of cooling tower's intake eliminated.

Since there is a defined amount of discharged air flow from a cooling tower, VAWTs are mounted on top of the cooling tower to utilize the discharged air kinetic energy which is higher and more consistent as compared to the natural wind. The same concept is applied to the turbocharger in car engine. In a normal engine the exhaust gas from engine is a waste and dissipated to the environment. In an engine with turbocharger, the turbocharger uses the exhaust flow from the engine to spin a turbine, which in turn spins an air pump [19]. The power generated is used to boost the engine performance. The same concept was used where the waste exhaust air discharged from a cooling tower is used to spin a turbine for energy recovery.

The entire designed system is held by a supporting structure and it can be mounted either in a horizontal or a vertical orientation without blocking the discharged air flow. The installation position of the system depends on the oncoming discharged air direction to the VAWTs. The whole system is installed horizontally with the supporting structure at both ends of the transmission shaft of the VAWT (bearing at a side and generator at the other side) where the discharged air is blown from beneath in a vertical direction. In contrary, under the condition of discharged air blowing sideways, the system can be installed vertically with the generator situated on the floor. With the aim of the designed system not causing negative impacts on the cooling tower performance, a predefined optimum position above the cooling tower's outlet is identified based on discharged air speed profile for placement of the two VAWTs.

The VAWTs are integrated with an enclosure which fitted with several guide-vanes together with two diffuser-plates as power-augmentation features to maximize the wind power generation. Guide-vanes are arranged in between the VAWTs and cooling tower's outlet at a predefined angle to form multiple air flow channels which are advantageous in terms of efficiency as the airflow are smoothened and matched to the optimum blade angle of the VAWTs. At the same time, the area of the wind passing through the guide-vanes is altered causing more airflow volume and hence, higher velocity flow into the optimum angle of VAWTs. As a result,