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Conceptual development of an energy recovery from the chimney flue gases using ducted turbine system

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ABSTRACT

An innovative idea of extracting kinetic energy from man-made wind resources (chimney flue gases) with ducted horizontal axis turbine system for producing electricity is introduced in this paper. The turbine system is positioned beyond the chimney outlet, to avoid any negative impact on the chimney performance. The duct acts as a safety cover for the energy recovery system and also enhances the performance of the system. The effect of airfoils NACA4412 and NACA4416 on the power extraction by the energy recovery system using a 6-bladed ducted turbine has been studied using CFD simulation. It is observed that the average flue gas velocity in the duct section at the throat is approximately twice that of the inlet velocity, whereas maximum throat velocity achieved is 2.6 times the inlet velocity. The results from the CFD (Computational Fluid Dynamics) based simulations analysis indicate that a significant power can be harnessed from the chimney exhaust. The system may be retrofitted to existing chimneys of thermal power plants, refineries and other industries. The market potential for this energy recovery system appears to be very high due to abundant chimneys, cooling towers and other man-made air/gaseous exhaust system present globally.

1. Introduction

More than 90% of the global electricity generation is contributed by the usage of coal and natural gas (Chilugodu et al., 2012). The availability of limited fossil fuel resources and increase in energy demand, has resulted in continuous efforts to establish more innovative energy generation systems which are better in terms of performance and economy. Many un-natural wind resources are being developed globally for useful power generation, like solar chimney exhausts (Chikere et al., 2011), wind energy harvest atop fast moving trains (Chilugodu et al., 2012), ventilated exhaust from air conditioning system (Goh and Duan, 2013), etc.

The total installed capacity of thermal power plants in India by the end March 2014 has been about 199,947 MW (Energy Statistics, 2015) against the global capacity 1,218,175 MW (Global Energy Observatory, 2015). A chimney of a typical thermal power plant (660 MW) has been observed to release exhaust flue gases with density, $\rho = 0.816$ kg/m^3 at an average velocity, $V = 22$ m/s having flow rate, $\dot{m} = 3{,}500{,}000$ m^3/hour. This data gives an idea of potential of energy that can be extracted from flue gases. Beside the thermal power plant chimneys, flue gases are available in industries, mills, brick kiln, etc. Thus chimney flue gases can be considered an important source of energy. The kinetic energy of the flue gases can be extracted for electricity generation. The chimney exhaust usually has a strong and consistent speed as compared to the natural wind, (an average wind speed of 5 m/s is sufficient to generate power, Chilugodu et al., 2012). Moreover, the chimney exhaust is usually available in almost every part of the world unlike the availability of natural wind resources.

The research method comprises of analysis of the flow field of flue gases using Computational Fluid Dynamics (CFD). The main purpose of the proposed research is to extract kinetic energy from the exhaust flue gases without putting any negative impact on the performance of the original exhaust system.

The contents of the paper have been arranged as follows: Section 2 presents a brief review of research in relevant areas. A brief discussion on proposed energy recovery system has been included in Section 3. Discussion on various aspects of computational modeling and CFD based analysis has been given in Section 4. Section 5 presents a brief discussion on simulated results. The last section presents concluding remarks along with directions for future work.

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2. Literature review

The concept of extracting kinetic energy from chimney flue gases appears to be a novel one. The research literature directly related to the topic is hardly available. Considering the proposed concept of energy extraction from flue gases, analogous to wind energy conversion system, the literature review is mainly focused on (a) the ducted wind turbine system and (b) the unnatural wind energy systems.

2.1. Improvement of output power using ducted turbines

The wind speed is considered to be low and the direction to be inconsistent throughout the year. As a result, harnessing wind energy with conventional wind turbines is not only difficult but also inefficient. In 1919, Betz formulated a criterion known as Betz limit according to which the maximum power coefficient that can be attained by wind turbine under ideal conditions is about 59% (Wang and Chen, 2007). A brief discussion in this regard has been presented in Appendix-A. Many researchers made efforts to increase the efficiency of the wind turbine. Even the efficiency of a well-designed turbine lies in the range of 35–45%. As the wind power is directly proportional to the cube of approaching wind velocity to a wind turbine (Manwell et al., 2002), even a slight acceleration in wind speed, will cause a large increase in the power output. Hence, numerous attempts have been made to improve the approaching wind speed effectively. One of the promising concepts employed for the purpose is the Diffuser-Augmented Wind Turbine (DAWT). The experimental study conducted by Foreman et al. (1978) indicates that the wind power extraction capability for DAWTs is almost double as compared to that of conventional turbines.

Lawn (2003) analyzed the performance of a shrouded turbine with efficient controlled diffusion at outlet using one-dimensional theory. Bet and Grassmann (2003), Grant and Kelly, (2003), Abe et al. (2005), Matsushima et al. (2006), Grant et al. (2008), Ohya et al. (2008) and Isensee and Razzak (2012) conducted similar experimental and simulation study of a ducted (shrouded) wind turbines, and showed that the power output increases as compared to that obtained using bare wind turbines. It has been observed that the wind speed is greatly influenced by the length and angle of the diffuser. Van Bussel (2007) reviewed the experiments and theory of DAWT and noted that the power augmentation is proportional to the mass flow increase. Hansen (2008) showed that the relative increase in the power coefficient for a shrouded turbine is proportional to the ratio of the mass flow through the shrouded turbine to that through the bare turbine. Hu and Cheng (2008) proposed a bucket shaped ducted wind turbine to increase the power extraction efficiency up to 80%.

Balabel et al. (2011) presented the numerical simulation of compressible flow through a 2D convergent–divergent nozzle with different pressure ratios and tested several turbulence models. Costa Rocha et al. (2014) studied the calibration of k-ω SST (shear stress transport) turbulence model on a prototype of three-blade wind turbine designed for fixed tip-speed ratio ($\lambda = 5$). Chen et al. (2012) investigated the effect of flanged diffusers on rotor performance of small (30 cm rotor diameter) wind turbines with different rotor solidities (20–60%) and wind speeds (10–20 m/s). The experimental results show that the rotor speed, power and torque outputs increase significantly with flanged diffusers, depending on the rotor solidity and wind speed.

Chaudhari et al. (2013) studied the behavior of air flow through venturi using ANSYS FLUENT 14.0, to imitate the improvement of the kinetic energy by increasing the wind velocity, for increased power output of the turbine even with low input wind velocity. Wang et al. (2013) and Aranake et al. (2013) performed computational analysis of diffuser-augmented turbines to verify the benefit of increased mass flow through the turbine. Result shows substantial (up to 90%) improvement in power extraction, which is beyond the Betz limit. Karthikeyan et al. (2015) recently studied various blade profiles and airfoil geometry to achieve higher power coefficient in small horizontal axis wind turbines.

Monteiro et al. (2013) conducted several wind tunnel tests of a full scale horizontal axis wind turbine and compared the results with those predicted by WT-Perf and Qblade Blade Element Momentum (BEM) codes. It was further observed that the tip speed ratio varies inversely with the wind speed. Ahmed and Cameron (2014) studied the existing and emerging wind power technologies and the challenges being faced in this energy sector. Xu et al. (2014) designed and fabricated a miniature horizontal axis wind turbine (MHAWT), for multipurpose application, with and without gear transmission.

2.2. Extraction of kinetic energy from un-natural wind resources

The industrial chimneys and cooling towers appears to be the good candidates for un-natural (man-made) wind power extraction systems. Industrial chimneys play an important role to flush out the waste hot flue gases from combustion chamber into outside atmosphere. The hot flue gases are forced out from the outlet of the chimney with the assistance of power-driven fans. As the flue gases at the chimney outlet are exhausted in the range of 20–25 m/s, the kinetic energy of these hot flue gases may be extracted using a turbine and generating the electrical energy. The possibilities in this area are yet to be explored.

Chong et al. (2011) recorded that the velocity of exhaust air can go up to 18 m/s at a distance of 0.3 m above the cooling tower outlet, which can effectively be utilized for generation of clean energy. Venkatesh (2006) analyzed the power extraction from the exhaust gases of the automobile engine by replacing the radial flow with axial flow impulse turbine and observed improvement in power output. Peer and Prabhakar (2012) presented the concept of exhaust air kinetic recovery (e.g. industrial ventilation) by installing fans/turbines, and waste heat recovery (e.g. industrial hot air/exhaust from gases) for heating feed water in boilers, to improve the quality of environment. Chong et al. (2013 & 2014) proposed that the exhaust air from the cooling tower can effectively be utilized for generation of clean energy. The turbine system is expected to recover 13% of the power consumption. Hasan et al. (2013) and Patnaik and Ali (2013) presented theoretical concept of power generation from the waste wind energy of industrial exhaust fans.

The literature review reveals that the kinetic energy of chimney flue gases may usefully be extracted analogous to other unnatural wind resources, for the development of the proposed energy recovery system. Further, the research literature shows that the ducted turbine can enhance performance characteristics and improve the efficiency. The geometry of a duct significantly affects the performance of the turbine. The main emphasis of the research studies has been to increase the velocity and mass flow rate of the fluid to interact with the turbine rotor. Hence, the ducted turbine technology may be used to increase the velocity and mass flow rate of the flue gases for increased energy extraction. Further, the literature review also reveals that the computational modeling & simulation can be a valuable tool for the proposed study.

The power extraction from the chimney flue gases using the ducted turbine appears to be a very interesting and promising topic for research. This paper presents an energy recovery system to harness the kinetic energy of chimney flue gases for producing electricity using ducted turbine.