Chin. J. Mech. Eng. (2017) 30:472–482
DOI 10.1007/s10033-017-0090-8

ORIGINAL ARTICLE

Kinetic Energy Recovery from the Chimney Flue Gases Using Ducted Turbine System

Harjeet S. Mann[1] · **Pradeep K. Singh**[1]

Received: 16 March 2016 / Revised: 15 November 2016 / Accepted: 20 January 2017 / Published online: 14 March 2017
© Chinese Mechanical Engineering Society and Springer-Verlag Berlin Heidelberg 2017

Abstract An innovative idea of extracting kinetic energy from man-made wind resources using ducted turbine system for on-site power generation is introduced in this paper. A horizontal axis ducted turbine is attached to the top of the chimney to harness the kinetic energy of flue gases for producing electricity. The turbine system is positioned beyond the chimney outlet, to avoid any negative impact on the chimney performance. The convergent-divergent duct causes increase in the flue gas velocity and hence enhances the performance of the turbine. It also acts as a safety cover to the energy recovery system. The results from the CFD based simulation analysis indicate that significant power 34 kW can be harnessed from the chimney exhaust. The effect of airfoils NACA4412 and NACA4416 and the diffuser angle on the power extraction by the energy recovery system using a 6-bladed ducted turbine has been studied with the 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 velocity achieved is 2.6 times the inlet velocity. The simulated results show that about power may be extracted from the chimney flue gases of 660 MW power plant. The system can be retrofitted to existing chimneys of thermal power plants, refineries and other industries.

Keywords Chimney flue gases · Energy recovery system · Kinetic energy · Ducted turbine · CFD

Nomenclature

V	Average velocity of flue gases
$\dot{m}$	Mass flow rate of flue gases
ρ	Flue gas density
U	Free stream velocity
T	Temperature of flue gases at inlet
P_1	Pressure of flue gases at duct inlet
P_2	Atmospheric Pressure of flue gases
u, v, w	Velocity components of flue gases
R	Turbine rotor radius
ω	Angular velocity, rate of eddy dissipation
P	Power
τ	Torque
C_T	Coefficient of torque
C_P	Coefficient of power
λ	Tip speed ratio
η	Efficiency
α	Angle of attack
θ	Diffuser angle
q	Heat transfer
k	Variance of velocity fluctuations
ε	Turbulence eddy dissipation

1 Introduction

More than 90% of the global electricity generation is contributed by the usage of coal and natural gas (Chilugodu, et al [1]). Application of these fossil fuels invariably causes environmental pollution and therefore dependence on these energy sources needs to be curtailed. The urgent need for alternative energy resources due to 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. The solar

---

✉ Pradeep K. Singh
pkschauhan@yahoo.com

[1] Department of Mechanical Engineering, Sant Longowal Institute of Engineering and Technology, Longowal, Punjab 148106, India

and the wind energy resources are the fastest growing energy resources. There is a need for the innovative methods to address the issues encountered in harvesting natural and unnatural wind resources. An average wind speed of 5 m/s is sufficient to generate power [1]. There are many un-natural wind power sources present globally. Recent research reported include solar chimney exhausts (Chikere, et al [2]), harvesting wind energy from fast moving trains [1], ventilated exhaust from air conditioning system (Goh & Duan [3]), etc.

The 3 R-principle “Reduce, Reuse, Recycle” is definitely important for saving the environment. Here a fourth R is being added to the string, namely ‘Recovery’, which is actually more or less related to the combination of ‘Reuse’ and ‘Recycle’ (Fig. 1). A chimney of a typical thermal power plant (660 MW) has been observed to release exhaust flue gases with density, ρ=0.816 kg/m^3 at an average velocity, V=22 m/s having flow rate, $\dot{m}$=3500000 m^3/h. The chimney exhaust usually has a strong and consistent speed unlike the natural wind. Also, the chimney exhaust is usually available in almost every part of the world unlike the availability of natural wind resources. The kinetic energy of the chimney flue gases can be extracted for electricity generation.

The concept of generating power from the kinetic energy of 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 relevant literature related to wind energy conversion system is reviewed.

The wind power is directly proportional to the cube of approaching wind velocity to wind turbine (Manwell, et al [4]). Thus even a slight surge 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).

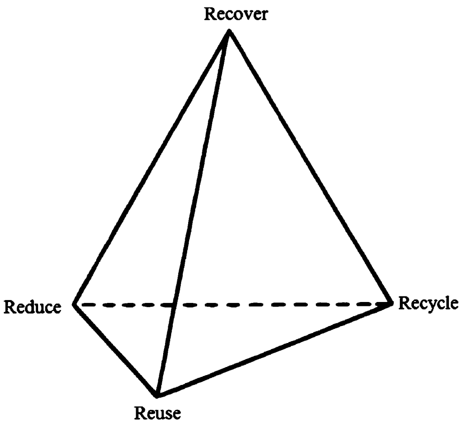


Fig. 1 Representation of 4 R’s concept

The experimental study conducted by Foreman, et al [5] indicates that the wind power extraction capability for DAWTs is almost double as compared to that of conventional turbines. Lawn [6], Bet, et al [7], Grant, et al [8, 9], Abe, et al [10], Matsushima, et al [11], Ohya, et al [12] and Isensee, et al [13] conducted similar experimental and simulation studies of ducted (shrouded) wind turbines, and showed that the power output increases as compared to that obtained using bare wind turbines. Van Bussel [14] reviewed the experiments and theory of DAWT and observed that the power augmentation is proportional to the mass flow increase. Hansen [15] 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, et al [16], proposed a bucket shaped ducted wind turbine to increase the power extraction efficiency.

Chen, et al [17], 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. The length and angle of the diffuser also influence the wind speed to a great extent. Thus geometry of a duct appears to significantly affect the performance of the turbine

Chaudhari, et al [18], studied the behaviour of air flow through venturi using ANSYS FLUENT 14.0, to imitate the improvement of kinetic energy resulting from increase in the wind velocity. Wang, et al [19] and Aranake, et al [20] 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.

Monteiro, et al [21], observed that the tip speed ratio varies inversely with the wind speed. Ahmed, et al [22], presented a detailed review based on the studies on the existing and emerging wind power technologies, and the challenges being faced in this energy sector.

The industrial chimneys and cooling towers appear to be the good candidates for un-natural (man-made) wind energy systems. The hot flue gases are forced out through chimney exit, with the assistance of power-driven fans, in the range of 20-25 m/s. The kinetic energy available with flue gases may be extracted for generating the electrical energy using a ducted turbine.

Venkatesh [23] analyzed the power extraction from the exhaust gases of the automobile engine. Peer, et al [24], presented the concept of exhaust air kinetic recovery (e.g., industrial ventilation) by installing fans/turbines. Hasan, et al [25] and Patnaik, et al [26], presented theoretical concept of power generation from the waste wind energy of industrial exhaust fans. Chong, et al [27–29], 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.

The literature review reveals that the kinetic energy of chimney flue gases may usefully be extracted for the development of the proposed energy recovery system. 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 modelling & 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. The research method comprises an analysis of the flow field of flue gases using computational fluid dynamics (CFD). This paper presents an energy recovery system to harness the kinetic energy of chimney flue gases for producing electricity using ducted turbine, without putting any negative impact on the performance of the original exhaust system.

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

2 Proposed Energy Recovery System

As discussed above, the installation of a turbine at the outlet of chimneys can recover a portion of the kinetic energy of exhaust flue gases for power generation. The flue gas speed is almost constant (20-25 m/s) and generally more than the natural wind speed (average wind speeds on land is 5.5 m/s and offshore is 6.5 m/s).Thus, the chimney exhaust can generate more power than that produced from natural wind. The proposed energy recovery system involves a duct (convergent-divergent) to form an enclosure for the turbine above the chimney outlet to extract the kinetic energy of flue gases. The proposed system appears to have a great potential due to ample number of chimneys available in industries and thermal power plants.

There are plenty of sources of flue gases in thermal power plants, paper mills, sugar mills, rice mills, refineries, diesel power plants, etc. This energy recovery system can be implemented without making major changes in the existing infrastructure. However, the energy recovery system should be placed at chimney outlet, to minimize any adverse effects on chimney exhaust and the chimney efficiency. The analysis of the proposed system is based on the computational fluid dynamics (CFD). The simulation study is necessary for development of design specifications of the energy recovery system to build it sturdy, so as to withstand wind forces involved, and to operate at maximum efficiency.

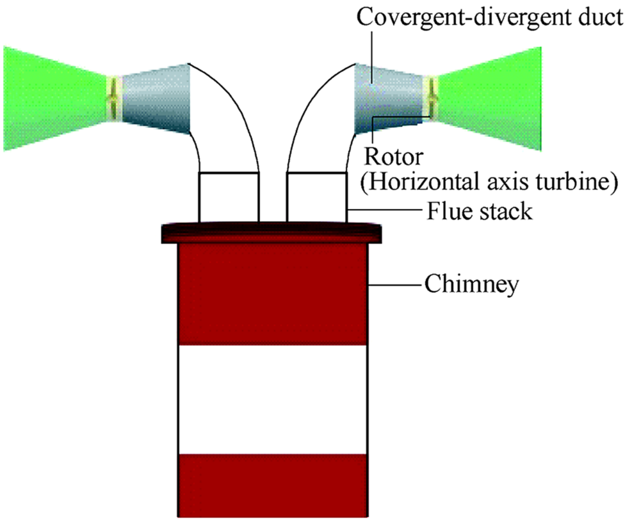


Fig. 2 General arrangement of the proposed (exhaust flue gases) energy recovery system

2.1 General Arrangement and Working Principle

Design of the proposed exhaust energy recovery system is based on the Bernoulli's principle and the horizontal axis wind turbine operating characteristics. The general arrangement of the proposed system can be illustrated in Fig. 2. A ducted horizontal axis turbine (HAT) integrated with suitable pipe bends is mounted above a chimney exit through a supporting structure to extract the kinetic energy of flue gases.

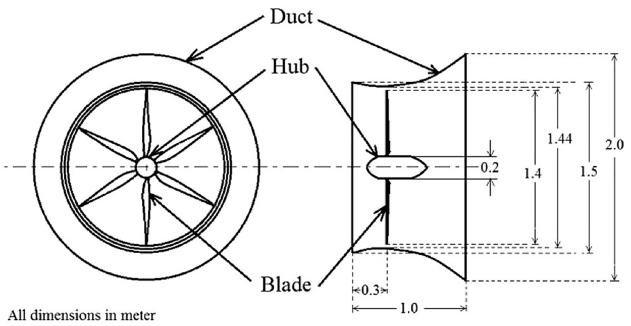


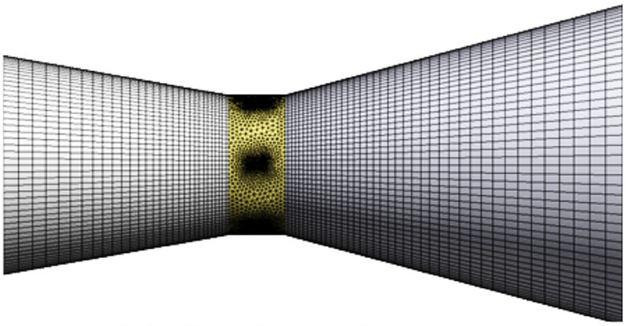
Fig. 3 Overall ducted turbine system for energy recovery [31]

The venturi effect of the duct (convergent-divergent type) significantly increases the velocity of flue gases and hence maximizes the energy recovery from the flue gases. The duct also guides the flue gases at an optimum angle of attack before it encounters the rotor. Hence, increases the rotational speed of the turbine and improves the power generation. Further, low pressure zone developed around the turbine rotor can even induce more flue gases to pass through the rotor resulting in more power generation.

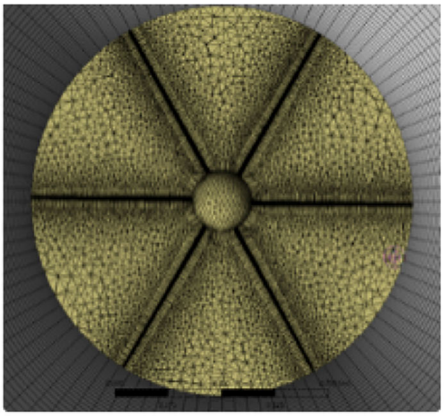
The use of diffuser not only increases the power extraction but also provides safety cover to the turbine rotor and generator from the adverse environmental conditions. The duct reduces the possibility of accidents due to blade failure, and the possibility of birds striking the turbine blades. The duct also moderates the noise level of the turbine.

2.2 Additional Features

This proposed energy recovery system targets at generating on-site energy by converting waste kinetic energy from chimney flue gases to the useful electrical energy. The exhaust flue gases can in general be characterized with continuous, consistent and constant flow. Thus, the energy generated from flue gases can be easily predicted. The turbine is expected to rotate at almost constant velocity with nominal fluctuation and therefore, the speed control system is not required. Hence, the lifespan of the turbine is expected to be longer than that of the wind turbine (i.e., 20 years, Martinez, et al [30]). Also, the proposed system does not need any extra land area for the installation, and thus makes it advantageous compared to the conventional wind turbine systems.



(a) Complete mesh system



(b) Enlarged side view of turbine rotor

Fig. 4 Meshing system of ducted turbine system

3 Computational Modeling

The flow of flue gases through the ducted turbine system has been simulated. Three-dimensional (3D) discretization has been employed with the finite volume method (FVM) using ANSYS 14.5 to investigate the power generation through system. The ducted turbine system modeled in this study is based on Wang, et al [31] (Fig. 3). Computational modeling has been carried out on the model composed of the duct (convergent-divergent type), rotor, blades, and hub with a generator.

Two different types of airfoils namely, NACA4412 and NACA4416 have been taken for blade profile, to study their effect on the power generation. The NACA4412 has the highest lift/drag ratio at approximately 7° angle of attack [31], and therefore all sectional incidence angles of the blade profiles have been set at 7°.

The study and analysis has been carried out on computer system with configuration of i7 2600 CPU@ 3.40 GHz having 8 GB RAM and 64 bit Windows 7 Professional operating system using ANSYS 14.5 to model the flow of flue gases through the ducted turbine mounted at the exit of the chimney.

3.1 Mesh System

Meshing grid has been generated in TurboGrid 14.5. First, the surface of the duct is meshed with quad element. In order to resolve the turbulent boundary layer on the solid surfaces, the best approach is to have growing fine cells from the blade surfaces. Finally the remaining region in the domain is filled with tetrahedral cells. Special care has been taken to the zones close to the walls for the mesh generation. In the proximity of the rotor the mesh is finer than any other part of the domain. The complete grid for the system consists of 4.3 million elements. Different surface meshes are depicted in the Fig. 4.

For the computational domain, the Multi Reference Frames (MRF) approach has been adopted for the flue gases passing through turbine rotor. Two reference frames namely, stationary frame (relative to the duct walls) and the moving frame (relative to the turbine rotor) have been considered. Further, the fluid zone is also divided into two separate regions, (a) stationary zone, related to the flow of gases, and (b) moving zone, close to the rotating turbine.

3.2 Boundary Conditions

The boundary conditions are the primary requirements for pre-processing. The flow velocity of chimney flue gases at inlet of the duct system for is set the inlet boundary condition. Other boundary conditions are set on the surrounding surface, i.e., duct surface and exit of the diffuser section. The solid wall boundary conditions are set on the blade and the hub surfaces of the rotor, and the duct surface. This specifies that the fluid (flue gases) cannot flow across the boundary. The axial symmetry boundary conditions are applied on the centerline for the side walls of the duct due to the less disruptive nature of flow. All the boundary conditions of the ducted energy recovery system are summarized in Table 1 and Fig. 5.

3.3 CFD Simulation

There are three methods of analysis: analytical, experimentation, and simulation (CFD based). The CFD constitutes an advanced approach in the philosophical study and development of the entire discipline of fluid dynamics. It appears to be an equal partner with pure theory and pure experiment in analysis and solution of fluid dynamics problems. The CFD software tools (solvers, pre- and post-processing utilities) enable to perform 'numerical experiments', i.e., computer simulations in a 'virtual flow laboratory'. The CFD analysis is the low cost method and is based on the fundamental governing equations of fluid dynamics – the continuity, momentum, and energy equations. These are the mathematical statements of three fundamental physical principles upon which all of fluid dynamics is based [32].

Simulation of the proposed kinetic energy recovery system has been carried out using ANSYS CFX. The numerical method follows solution of the Reynolds-Averaged Navier-Stokes (RANS) equations using finite volume method. The flow field mesh domain has been considered rotating. Accordingly the coordinate system of the numerical simulation has been considered fixed on the rotor coordinate system.

Table 1 Boundary Conditions of the Problem

COMPONENT	TYPE	VALUE
Duct Surface	Wall	q = 0 W/m^2; No-slip; u = v = w = 0
Hub	Wall	q = 0 W/m^2; No-slip; u = v = w = 0
Duct Inlet	Inlet Velocity	V_1 = 22 m/s T_1 = 140°C
Duct Outlet	Exit Pressure	Atm. Pressure (P_2 = 101325 Pa)

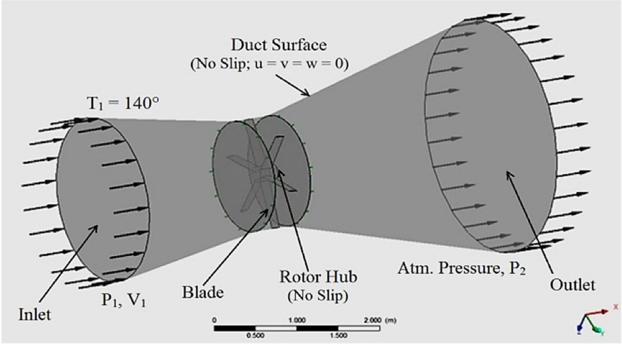
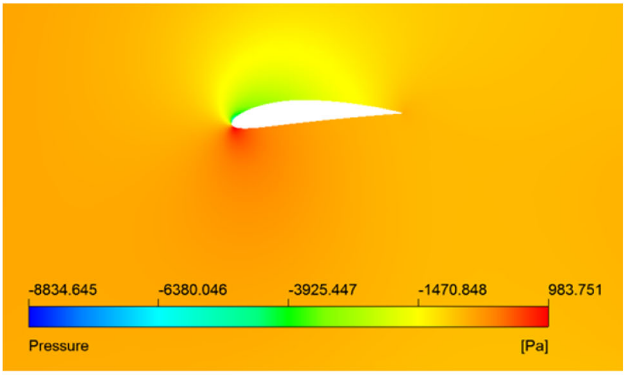
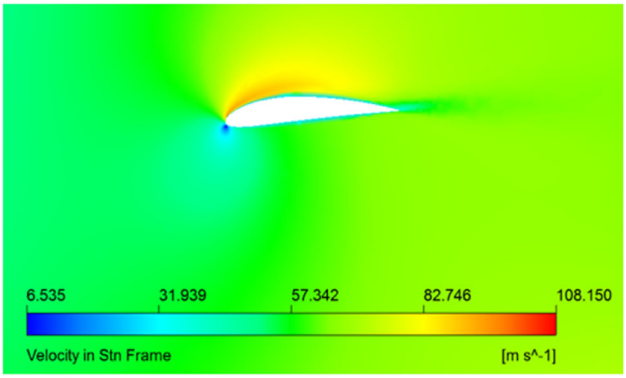


Fig. 5 Boundary conditions employed on energy recovery system

A turbulence model can be employed to predict the flow behavior in the proposed physical domain. The study reported by Balabel, et al [33] on testing of several turbulence models reveals that, the shear-stress transport k - ω (SSTk - ω) and the realizable v^2 - f models give the best



(a) Pressure distribution



(b) Velocity

Fig. 6 Flow characteristics around the blade at mid span with 6-bladed turbine in the duct with 14° diffuser angle

Table 2 Torque and power extracted from the flue gases

Blade profile	Parameters	Diffuser angle					
		6°	8°	10°	12°	14°	16°
NACA4412	Avg. exit velocity (m/s)	20.04	19.87	19.89	19.0	18.79	17.05
	Torque (N•m)	333.540	333.600	333.781	333.440	333.213	332.425
	Power (kW)	34.90763	34.98010	34.99145	34.98065	34.77809	34.60025
	Efficiency (%)	18.18	18.22	18.25	18.23	18.12	18.02
NACA4416	Avg. exit velocity (m/s)	22.9	22.45	20.75	19.79	19.54	16.25
	Torque (N•m)	330.455	330.590	333.595	333.750	331.891	330.425
	Power (kW)	34.55821	34.58472	34.82405	34.75190	34.51729	34.15620
	Efficiency (%)	18.00	18.01	18.14	18.11	17.98	17.79

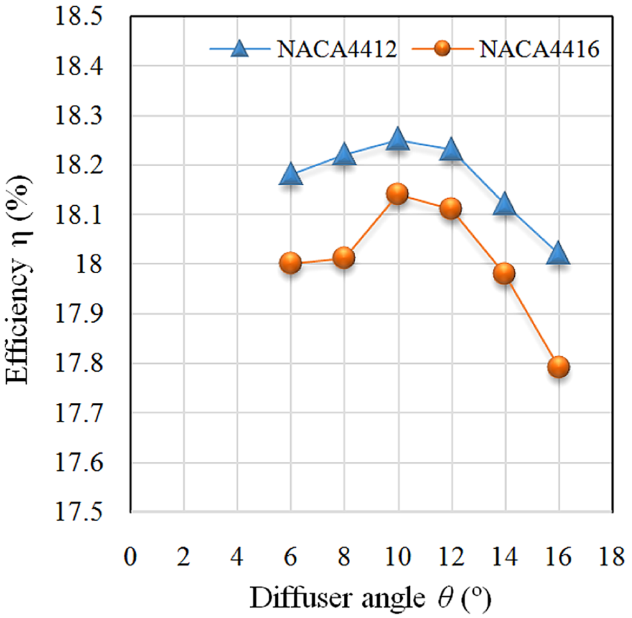
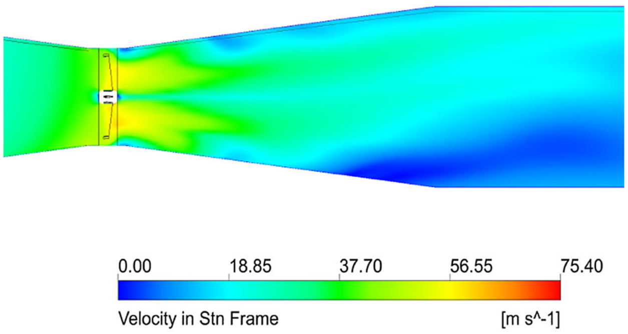
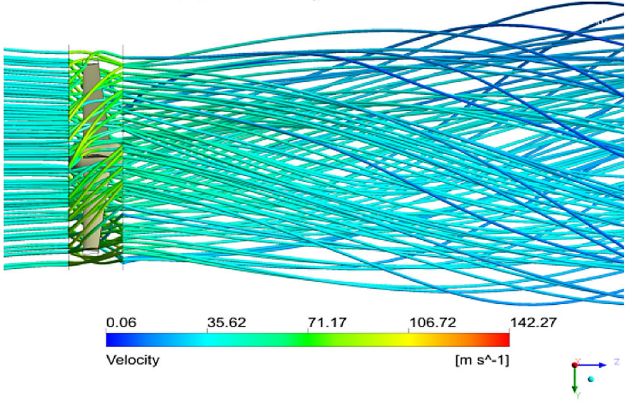


Fig. 7 Graph of diffuser angle vs efficiency



(a) Velocity contours



(b) Velocity streamlines contours

Fig. 8 Simulated result for NACA4412 at diffuser angle of 8°

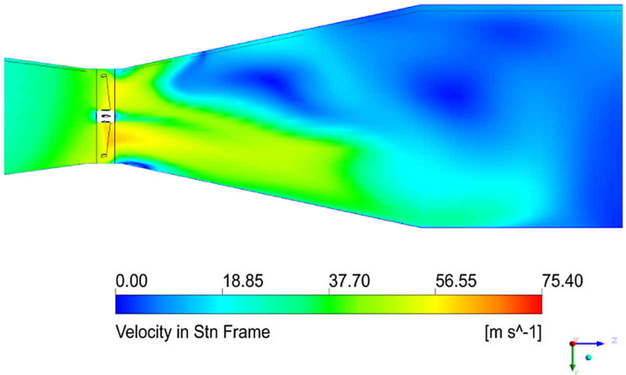
results in predicting the separation and shock wave position. Almost all these turbulence models are derived from standard $k - \varepsilon$ model by varying complexity and robustness. The $k - \varepsilon$ turbulent model proposed by Abe, et al [34] has been adopted to predict the complex turbulent flow field. The turbulence kinetic energy, k is defined as the variance of the fluctuations in velocity whereas turbulence eddy dissipation, ε is the rate at which the velocity fluctuations dissipate.

The proposed study to introduce the energy transformation from kinetic energy of chimney flue gases to mechanical energy of the ducted turbine. This in turn can be used for power generation. The CFD analysis also helps identify factors, such as interference, recirculation/back flow, etc. that significantly affect the performance of chimney exhausts.

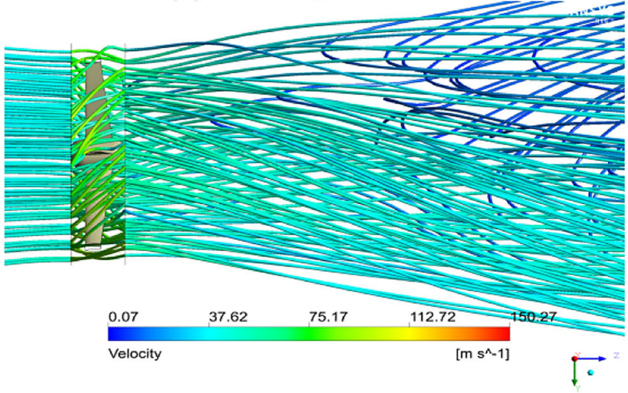
4 Results and Discussion

The thermal power plants produce exhaust flue gases at a velocity 20 m/s to 25 m/s following the environment protection constraints. A typical thermal power plant (660 MW) has been observed to release exhaust flue gases with following specifications:

Average velocity, V= 22 m/s,
Density, ρ =0.816 kg/m^3,
Flow rate, $\dot{m}$=3500000 m^3/h.

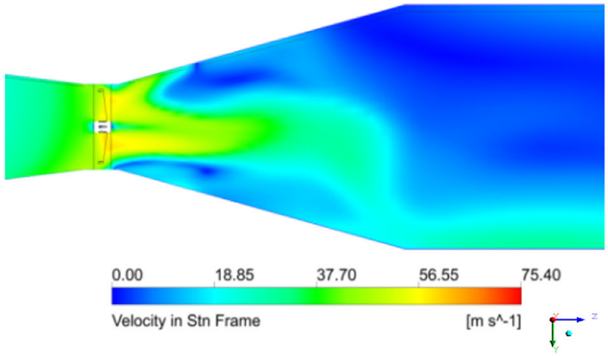


(a) Velocity contours

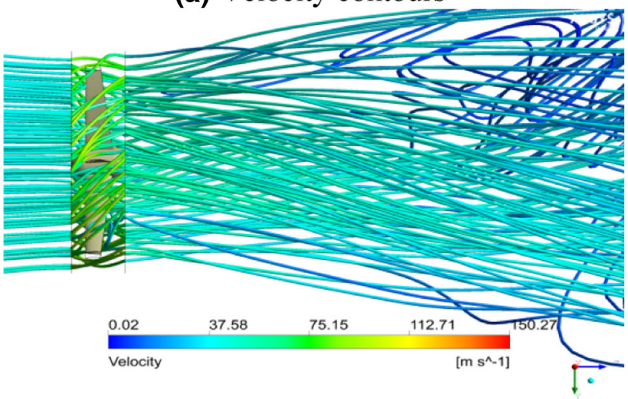


(b) Velocity streamlines contours

Fig. 9 Simulated result for NACA4412 at diffuser angle of 12°



(a) Velocity contours



(b) Velocity streamlines contours

Fig. 10 Simulated result for NACA4412 at diffuser angle of 14°

The flow field of flue gases with the ducted turbine and hub has been simulated using CFD. The flow of the exhaust flue gases from the chimney gets accelerated while passing through the duct and reaches the maximum velocity at the throat section. The result of the velocity and pressure distribution for the 6-bladed ducted turbine with 7° angle of attack (α) across the mid-section of the blade span are shown in Fig. 6. During simulation the diffuser angle (θ) has been varied from 6° to 16° in step of 2° with two type of airfoils, namely, NACA4412 and NACA4416 to investigate the effect on power generation.

The results show a gradual increase in pressure along the stream-wise direction within the rotor passage, with the higher pressure on the pressure side than that on the suction side of the rotor blade. However, the pressure developed inside the rotor is not so uniform. There could be a flow separation because of the pressure gradient effect. The velocity of flow also increases gradually along the stream-wise direction within the rotor passage. The separation of flow can be seen at the blade's leading edge. As the flow along the blade is neither tangential nor uniform, the separation of flow takes place along the surface of blade. Here it can be seen that the flow separation is takes place on both sides (i.e., pressure and suction side) of the blade as shown in Fig. 6.

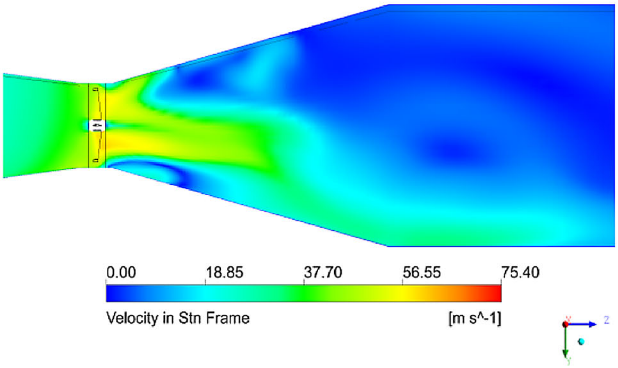
Further, the simulated results show the effect of diffuser angle and the different airfoil shapes on the torque developed and power produced corresponding to the flow of flue gases at 22 m/s inlet velocity through the ducted turbine system. The important performance parameters namely, tip speed ratio (TSR), power (P), and torque (τ) can be obtained:

$$TSR, \lambda = \frac{\text{Linear speed of the blade's outermost tip}}{\text{Free upstream velocity}} = \frac{R\omega}{U} \tag{1}$$

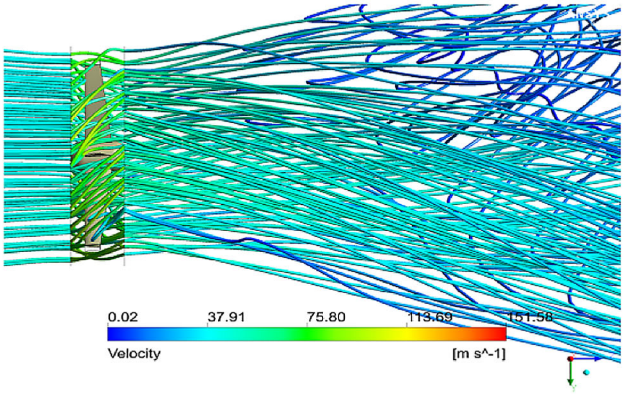
$$P = \frac{1}{2} C_P \rho \pi R^2 V^3 \tag{2}$$

$$\tau = \frac{1}{2} C_T \rho \pi R^3 V^2 \tag{3}$$

The simulated results for torque and power generated, and efficiency obtained for both the airfoils, i.e.,

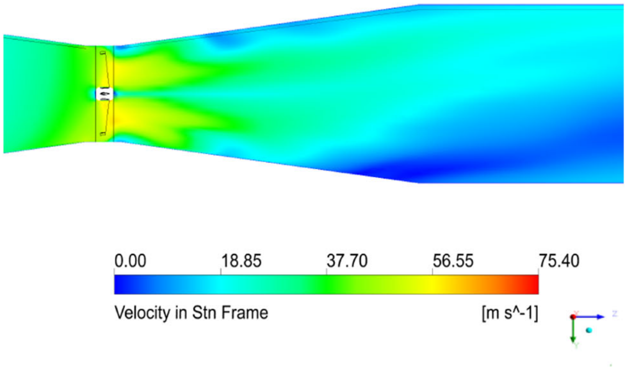


(a) Velocity contours

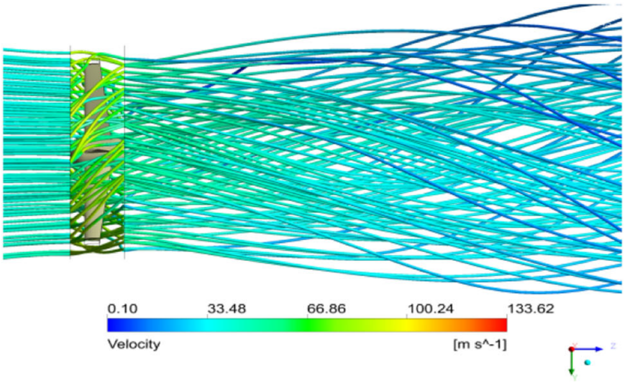


(b) Velocity streamlines contours

Fig. 11 Simulated result for NACA4412 at diffuser angle of 16°



(a) Velocity contours



(b) Velocity streamlines contours

Fig. 12 Simulated result for NACA4416 at diffuser angle of 8°

NACA4412 and NACA4416 with variation of diffuser angle are shown in Table 2. The variation of the torque and output power with diffuser angle appears to be nominal, with the highest value occurring at around 10° for both the airfoil shapes. The airfoil NACA4412 appears to produce slightly more torque & power as compared to the airfoil NACA4416. Also, the exit velocity of the flue gases appears to decrease with the diffuser angle throughout.

The efficiency of the energy recovery system is the ratio of kinetic energy recovered by the ducted turbine system to the kinetic energy available with the flue gases:

$$\eta = \frac{\text{Kinetic Energy Recovered (Power Extracted)}}{\text{Kinetic Energy available in the Flue Gases}} \tag{4}$$

Kinetic energy available in the chimney flue gases

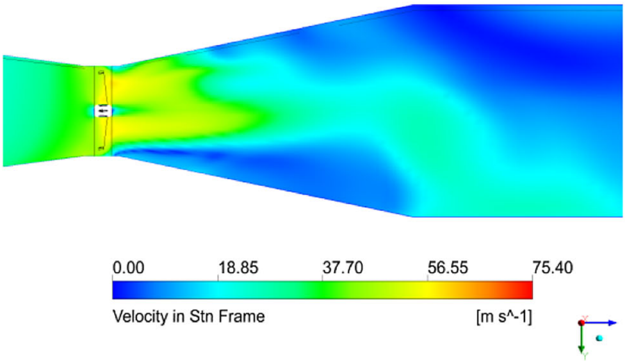
$$\begin{aligned} KE_{\text{fluegases}} &= \frac{1}{2}\dot{m}V^2 = 191986.67\ \text{J/s} \\ &= 191.986\ \text{kW} \end{aligned}$$

The variation of the efficiency with diffuser angle is shown in Fig. 7. The maximum efficiency appears to occur at around 10° diffuser angle for both the airfoils (NACA4412 & NACA4416). The airfoil NACA4412 appears to yield efficiency slightly higher than that by the airfoil NACA4416 for the complete range of diffuser angle.

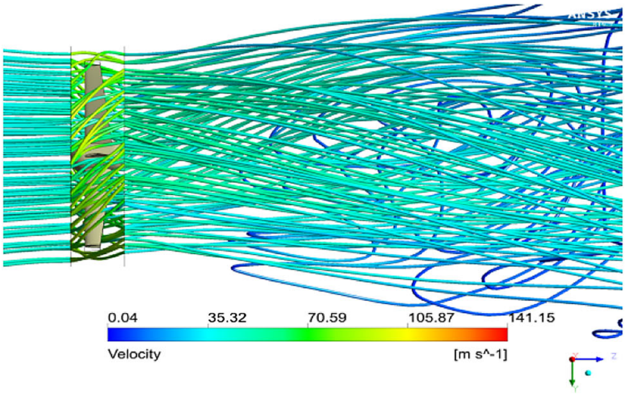
The possible reason for the lower efficiency at smaller diffuser angle (less than 10°) can be the less flow rate of flue gases. On the other hand, reduced efficiency at larger values of diffuser angle (beyond 10°) can be due to the formation of eddies and flow separation.

The power extracted from the flue gases using a ducted turbine is related to the diffuser size, rotating speed and velocity of flue gases (which is constant in this case). Figs. 8, 9, 10, 11 show the velocity contours and velocity streams of flue gas through the ducted turbine having 6-blade of airfoil NACA4412. It is observed that the axial velocity of the flue gases across the turbine, i.e., at the throat, is greater than that at the duct inlet. It means more mass flow of flue gases is drawn by the turbine and in turn more power can be extracted from the flue gases.

Figs. 12, 13, 14, 15 shows the velocity contours and velocity streams of flue gas through the ducted turbine having 6-blade of airfoil NACA4416. Further, backflow is

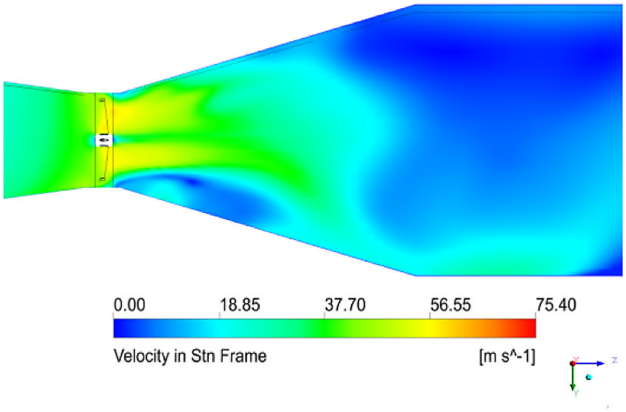


(a) Velocity contours

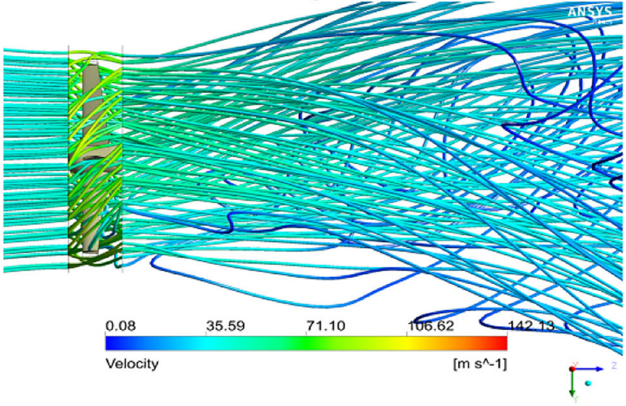


(b) Velocity streamlines contours

Fig. 13 Simulated result for NACA4416 at diffuser angle of 12°



(a) Velocity contours



(b) Velocity streamlines contours

Fig. 14 Simulated result for NACA4416 at diffuser angle of 14°

observed in both cases of airfoil for the diffuser angle starting with 12°, but it appears to be more predominant for the NACA4416. The Backflow in the duct adversely affects the power generation efficiency of turbine as well as the performance of chimney exhaust.

5 Conclusions and Future Scope

Industrial exhaust and chimney flue gases can be considered as a high velocity man-made wind resources. The proposed energy recovery ducted turbine system is helpful in extracting the kinetic energy of the chimney flue gases and thus can contribute to the power at the site itself.

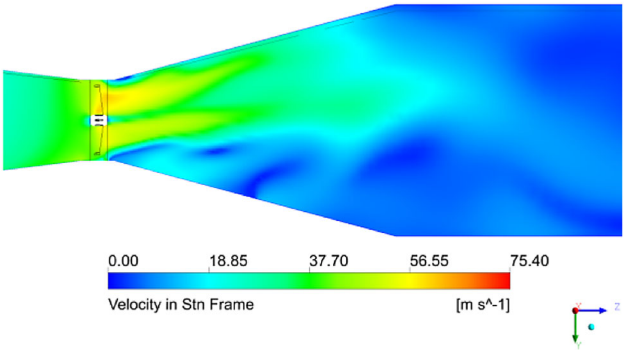
The results from the CFD based simulation analysis indicate that significant power can be harnessed from the chimney exhaust. The effect of airfoils NACA4412 and NACA4416 on a power extraction using a 6-blade ducted turbine has been studied. It is observed that the average flue gas velocity in the duct section at the throat is approximately twice that of the inlet velocity, whereas maximum velocity achieved is 2.6 times the inlet velocity.

The simulated results show that about 34 kW power may be extracted from the chimney flue gases of 660 MW power plant. The highest value of torque, power output and efficiency appears to occur at around 10° diffuser angle for both the airfoil shapes. The airfoil NACA4412 appears to perform slightly better than the airfoil NACA4416. Also, the exit velocity of the flue gases appears to decrease with the diffuser angle throughout.

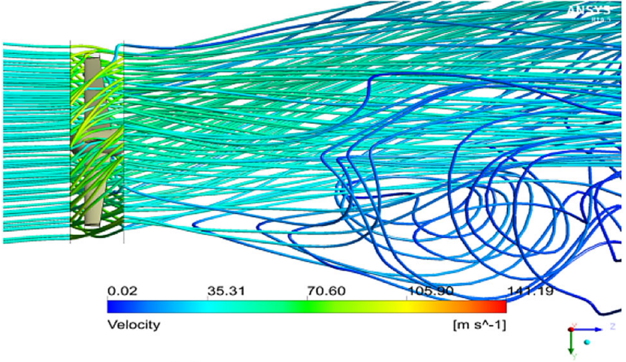
The proposed energy recovery system appears to have high market potential due to abundant chimneys and other unnatural exhaust wind resources available globally.

Future work of research can be conducted in line with this conceptual development of energy recovery ducted turbine system as follows:

(1) Comprehensive study of the effect of number of blades, airfoil shapes and angle of attack on the system performance and exhaust flue gases flow characteristics.



(a) Velocity contours



(b) Velocity streamlines contours

Fig. 15 Simulated result for NACA4416 at diffuser angle of 16°

(2) Study of the effect of flue gases backflow, if any, on the chimney's performance.
(3) Study on vertical axis ducted turbine system.
(4) Evaluating the feasibility study (economics) of integrating the energy recovery system atop the chimney.

Acknowledgement Authors would like to express gratitude to the anonymous reviewers for their useful comments for correction and improvement of the manuscript. The input given by Dr. K. Muralidhar of IIT, Kanpur, and Dr. Subhash Chander of NIT, Jalandhar in finalizing the area of research are gratefully acknowledged.

References

1. CHILUGODU N, YOON Y-J, CHUA KS, et al. Simulation of train induced forced wind draft for generating electrical power from Vertical Axis Wind Turbine (VAWT) [J]. *International Journal of Precision Engineering and Manufacturing*, 2012, 13(7): 1177–1181.
2. CHIKERE A O, AL-KAYIEM H H, ABDU Z A. Review on the enhancement techniques and introduction of an alternate enhancement techniques of solar chimney power plant [J]. *Journal of Applied Sciences*, 2011, 11(11): 1877–1884.
3. GOH K H, DUAN F. Performance of a prototype micro wind turbine in the manmade wind field from air conditioner of buildings [J]. *QScience Connect* 2013: 4.
4. MANWELL J F, MCGOWAN J G, ROGERS A L. *Wind Energy Explained: Theory, Design and Application*[M]. Chichester, England: John Wiley & Son Ltd., 2002.
5. FOREMAN K M, GILBERT B, OMAN R A. Diffuser augmentation of wind turbines[J]. *Solar Energy*, 1978, 20: 305–311.
6. LAWN C J. Optimization of the power output from ducted turbines [J]. *Journal of Power and Energy*, 2003, 217: 107–117.
7. BET F, GRASSMANN H. Upgrading conventional wind turbines [J]. *Renewable Energy*, 2003, 28(1): 71–78.
8. GRANT A, KELLY N. The development of a ducted wind turbine simulation model [C]//*8th International IBPSA Conference*, Eindhoven, Netherlands. August 11–14, 2003.
9. GRANT A, JOHNSTONE C, KELLY N. Urban wind energy conversion: The potential of ducted turbines [J]. *Renewable Energy*, 2008, 33: 1157–1163.
10. ABE K, NISHIDA M, SAKURAI A, et al. Experimental and numerical investigations of flow fields behind a small wind turbine with a flanged diffuser [J].*Journal of Wind Engineering and Industrial Aerodynamics*, 2005, 93:951–970.
11. MATSUSHIMA T, TAKAGI S, MUROYAMA S. Characteristics of a highly efficient propeller type small wind turbine with a diffuser[J]. *Renewable Energy*, 2006, 31: 1343–1354.
12. OHYA Y, KARASUDANI T, SAKURAI A, et al. Development of a shrouded wind turbine with a flanged diffuser[J]. *Journal of Wind Engineering and Industrial Aerodynamics*, 2008, 96: 524–539.
13. ISENSEE G M, RAZZAK H A. Modeling and analysis of diffuser augmented wind turbine[J]. *International Journal of Energy Science*, 2012, 2(3): 84–88.
14. Van BUSSEL G J W. The science of making more torque from wind: Diffuser experiments and theory revisited [J]. *Journal of Physics: Conference Series*, 2007, 75: 1–13.
15. HANSEN, M O L. *Aerodynamics of Wind Turbines* [B]. Sterling, VA: Earthscan, 2008.
16. HU S, CHENG J. Innovatory designs for ducted wind turbines [J]. *Renewable Energy*, 2008, 33: 1491–1498.
17. CHEN T Y, LIAO Y T, CHENG C C. Development of small wind turbines for moving vehicles: Effects of flanged diffusers on rotor performance [J]. *Experimental Thermal and Fluid Science*, 2012, 42: 136–142.
18. CHAUDHARI C D, WAGHMARE S A, KOTWAL A P. "Numerical analysis of venturi ducted horizontal axis wind turbine for efficient power generation [J]. *International Journal of Mechanical Engineering and Computer Applications*, 2013, 1(5): 90–93.
19. WANG J, PIECHNA J, MULLER N. Computational fluid dynamics investigation of a novel multiblade wind turbine in a duct [J]. *Journal of Solar Energy Engineering*, 2013, 135: 011007-1-6.
20. ARANAKE A C, LAKSHMINARAYAN V K, DURAISAMY K. Computational analysis of shrouded wind turbine configurations [C]//*51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, Grapevine (Dallas/Ft. Worth Region), Texas, January 7–10, 2013.
21. MONTEIRO J P, SILVESTRE M R, PIGGOTT H, et al. Wind tunnel testing of a horizontal axis wind turbine rotor and comparison with simulations from two Blade Element Momentum codes [J]. *Journal of Wind Engineering and Industrial Aerodynamics*, 2013, 123: 99–106.
22. AHMED N A, CAMERON M. The challenges and possible solutions of horizontal axis wind turbines as a clean energy solution for the future [J]. *Renewable and Sustainable Energy Reviews*, 2014, 38: 439–460.
23. VENKATESH G. Power production technique using exhaust gas from present automobiles via convergent-divergent nozzle [C]//

IEEE Conference on Electric and Hybrid Vehicles (ICEHV'06), Pune, India. December 18–20, 2006.

24. PEER A, PRABHAKAR G. Realization of exhaust air recovery and waste heat recovery systems for energy conservation and sustainable development [J]. *Journal of Energy Technologies and Policy*, 2012, 2(7): 39–43.
25. HASAN M A, HOSSAIN M T, PAUL R, et al. Producing electrical energy by using wastage wind energy from exhaust fans of industries [J]. *International Journal of Scientific & Engineering Research*, 2013, 4(8): 1184–1187.
26. PATNAIK A, ALI S M. Industrial exhaust fans as source of power [J]. *International Journal of Electrical, Electronics and Data Communication*, 2013, 1(9): 38–42.
27. CHONG W T, POH S C, FAZLIZAN A, et al. Exhaust air and wind energy recovery system for clean energy generation [C]// *2011International Conference on Environment and Industrial Innovation (IPCBEE 2011)*, Kuala Lumpur: IACSIT, Singapore, 2011.
28. CHONG W T, POH S C, FAZLIZAN A, et al. Early development of an energy recovery wind turbine generator for exhaust air system [J]. *Applied Energy*, 2013, 112: 568–575.
29. CHONG W T, HEW W P, YIP S Y, et al. The experimental study on the wind turbine's guide-vanes and diffuser of an exhaust air energy recovery system integrated with the cooling tower [J]. *Energy Conversion and Management*, 2014, 87: 145–155.
30. MARTINEZ E, SANZ F, PELLEGRINI S, et al. Life cycle assessment of a multi-megawatt wind turbine [J]. *Renewable Energy*, 2009, 34: 667–673.
31. WANG SH, CHEN SH. Blade design for a ducted wind turbine [C]//*The 9th Asian International Conference on Fluid Machinery*, Jeju, Korea, October 16–19, 2007.
32. ANDERSON (Jr.) J D. *Computational Fluid Dynamics* [B]. Singapore: McGraw-Hill Inc., 1995.
33. BALABEL A, HEGAB AM, NASR M, et al. Assessment of turbulence modeling for gas flow in two-dimensional convergent–divergent rocket nozzle [J]. *Applied Mathematical Modelling*, 2011, 35: 3408–3422.
34. ABE K, OHYA Y. An investigation of flow fields around flanged diffusers using CFD [J]. *Journal of Wind Engineering and Industrial Aerodynamics*, 2004, 92: 315–330.

Harjeet S. Mann is a PhD Research Scholar in Department of Mechanical Engineering at Sant Longowal Institute of Engineering and Technology (SLIET), Longowal, India. He has served as Assistant Professor in Department of Mechanical Engineering for 13 years at GTBKIET, Malout. He has received BE in Mechanical Engineering from BRD College of Engineering, Sewagram in 1994 and ME in Mechanical Engineering (specialization in Rotodynamics Machines) from Panjab Engineering College, Chandigarh in 1998. His research interests include wind energy, rotodynamics machines, alternate energy resources, energy conversion, waste energy management, hybrid power system, etc.

Pradeep K. Singh is a Professor of Mechanical Engineering, at Sant Longowal Institute of Engineering and Technology, Longowal, India. He has also served Encardio-rite Electronics (P) Ltd. Lucknow, and Scooters India Ltd. Lucknow for a small span of time. He received B. Tech. in Mechanical Engineering from the Institute of Engineering & Technology (IET), Lucknow, in 1990, M. Tech. in Mechanical Engineering (specialization in Production Engineering) from the Institute of Technology Banaras Hindu University (IT-BHU), Varanasi, in 1992, and Ph.D. in Mechanical Engineering from the Indian Institute of Technology (IIT), Roorkee, in 2005. He has more than 23-year of professional experience in teaching, industry and research. He has published more than 20 papers in international journals of repute. He has been a reviewer of several international journals, viz. *IIE Transactions*, *Computers in Industry*, *Computer Aided Design*, *Proc. IMechE (Part B) Journal of Engineering Manufacture*, *Journal of Material Processing Technology*, *Annals of Operations Research*, etc. He is an Associate Editor of the "*Insight Mechanical Engineering*". He has been the guest editor to *International Journal of Applied Engineering Research*, **5**(17), 2010, and *International Journal of Engineering Studies*, **2**(3), 2010. His research interests include tolerance design, design for manufacture and assembly, metal machining, advanced optimization of mechanical systems, modeling and simulation of mechanical systems, waste management and energy recovery, etc.