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Experimentelle Untersuchung von Gebäude-integrierten Windführungen mit Laser-Doppler- Anemometrie

Experimental Investigation of Building Integrated Duct flow using Laser Doppler Anemometry

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Abstract

Buildings in the urban area consume a major share of total electrical energy generated in Germany. Several studies have showed that incorporating wind turbines into the building structures can effectively generate green energy and can reduce carbon footprint. One of the potential configuration to produce wind energy from building is wind turbines installed within ducts through building. But there are numerous unresolved issues in terms of aerodynamic investigation of ducts. This paper focus to the wind tunnel modeling of building integrated ducts for wind energy investigation and recommendations for efficient duct geometry to obtain so. Different geometry of building integrated ducts were investigated with the help of Laser Doppler Anemometry to obtain wind velocity data. Kinetic energy of wind was calculated from this data and used to select the efficient duct geometry.

Introduction

How energy is generated and used remains an unresolved problem for the twenty first century. Demand is increasing and resources are being exhausted. Increased amount of power generation from fossil fuel resulting in higher Green House Gas (GHG) emission is a major concern in climate change. Adverse impact of GHG does not only deteriorate the human health but also adversely influence the water resources, ecosystems, food security and coastal systems. Several studies have showed that increased share of power generation from renewable energy sources can reduce significantly the present rate of GHG emission [see Moomaw 2011]. Moreover, finite reserve of usable fossil fuel (coal, oil, gas) price is increasing rapidly. To an extent, power production scenario is quite different for Germany where growing public opinion against nuclear power generation and subsequent phasing out of nuclear power plants by 2022 has boosted power production from coal (hard coal, lignite) and oil [see Mazur 2014]. One of the indications of such is that more than half of Germany's electricity was generated from coal in the first half of 2013 [see Mazur 2014]. On the contrary, wind energy has immense potential in emulating the gap between growing energy demand and energy price as the cost of wind energy is free. In practice wind farms are installed far away from the location where electricity is required. Insufficient transmission capacity between the generator and consumer is a concerned predicament in promoting wind power generation. Thus the concept of decentralized energy supply emerges as the solution of this exhausted grid capacity. For years decentralized energy was supplied through solar systems and biomass generation due to the rationale of technological availability and cheap installation process. Distribution level congestion identifies the requirement of electricity generation from the consumer level [see Ender 2014]. This experiment was designed to verify experimentally the idea of wind energy generation from building integrated ducts. However, to obtain necessary conclusion about the suitability of such choices, exhaustive research and analysis about the wind data of the region has to be conducted [see Ender 2014]. According to Dondi et al. 2002, "distributed generation can be defined as a generator with small capacity close to its load that is not part of a centralized generation system". Beside electricity demand for industrial use, buildings remain one of the largest consumer of the electricity. From the statistical representation of data from German Federal Ministry for Internal Affairs and Energy, buildings consume 28.9 % of the total energy supply [see 21 December 2012, Retrieved from www.efficiency-from-germany.com]. It is a cheaper option to utilize the buildings to act as a concentrator of the wind flow which can augment the flow velocity. Moreover, Buildings can be used as an alternative to the expensive full size tower required to install for wind turbines. According to Martens et al. 2006, even without modified architecture, to some extent it is possible to generate wind energy from the existing rectangular building shapes [Bluff body] in certain regions.

Methodology

Limitations imposed to this experiment are as follows:

- Models are single building models of conventional shape (rectangular) in the aerodynamic wind flow.
- Angle of attack at 0° for wind flow to the duct axis.
- Applied wind flow velocity is 5 m/s for all experiments.
- Duct geometry was confined within 4 different shapes.

Theoretically available wind power or the usable energy from the wind flow is obtained from $P = \frac{1}{2}\rho A v^3$, which is a derivation of Bernoulli Theorem. Slight variation in the flow velocity can alter the energy yield significantly as the magnitude of the flow velocity is to the power of three. As such, target variable for the experiment is velocity. Velocities with its longitudinal and vertical components were measured with Laser Doppler Anemometry LDA measurement technique. LDA can measure the horizontal and vertical component of the flow velocity. Time averaged mean velocity profiles at the locations were calculated using $\bar{u} = \sqrt{\bar{u}_x + \bar{u}_y}$. Horizontal and vertical components of the measured data were averaged on the time series using the equations as

$\bar{u}_x = 1/T \int u_x(t)\partial t$ and $\bar{u}_y = 1/T \int u_y(t)\,\partial t$. Turbulence intensity from the data measured was calculated using the equation below.

$$I \equiv \frac{\sqrt{{u'_x}^2 + {u'_y}^2}}{\bar{u}}$$

Meaning of the notations used for all these equations above is as follows: Where *P* stands for the theoretical power obtained from the wind flow [Watt], ρ is density of Air in kg/m^3, *v* is applied Flow velocity in m/s, *A* stands for cross sectional area of the duct in meters, $\bar{u}_x$ is horizontal component of mean velocity [m/s], $\bar{u}_y$ is vertical component of mean velocity [m/s], u_x' is longitudinal component of turbulent velocity fluctuation [m/s], u_y' is vertical component of turbulent velocity fluctuation [m/s] and *I* stands for Turbulence intensity expressed in percentage.

Often it is not possible to generate exact Reynolds number in wind tunnel as real scale flow for a real scale building. However, literature's suggested that exact matching of Reynolds number is not needed when minimum Reynolds number threshold exceed the minimum value in the order of 10^4 e.g distortion of the flow is considered negligible for $Re > 10^4$ [7]. Reynolds number for this experiment was obtained as $Re \approx 1.8 \times 10^5$. Temporal scale for measurement in the upstream and downstream flow are 0.005 and 0.05 subsequently. LDA measurements were taken at locations of vertical center line of both inlet and outlet of all models. Measurement grid had a progressive refinement as it reaches near the duct. There are 95 to 111 measuring grid points with a varying resolution of maximum $0.003\ m$ to $0.001\ m$ Height of the measurement grid is as same as the model height which is $0.15\ m$ above the surface of the test section.

Experimental Setup

Model exterior represents a very typical rectangular ten story building of $40m\ \times 30m\ \times 25m$ dimension [see Fig.1: (a)]. Four different duct geometries installed at the center of the building models with a length scale of $200{:}\,1$ were used for these measurements. Exact dimension and location of the duct can be comprehended from Fig.1: (b). Based on the hypothesis

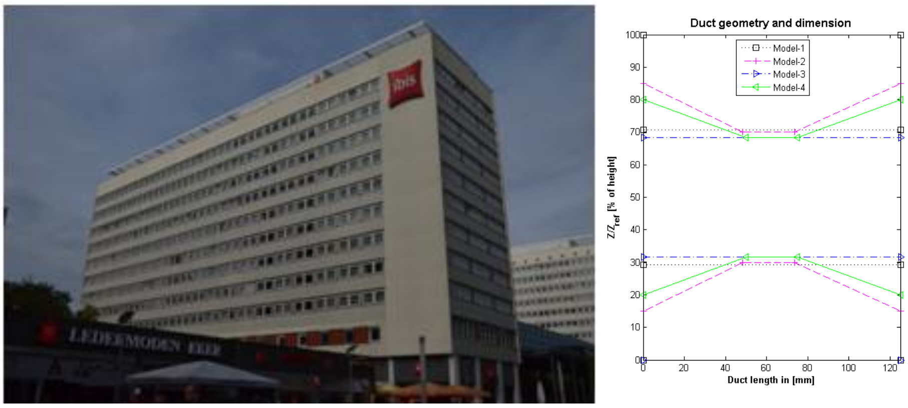
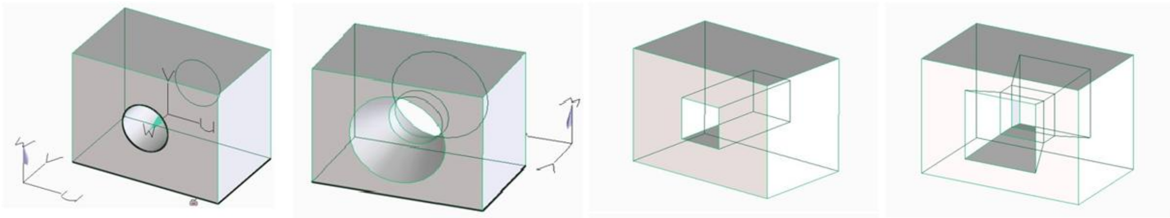


Fig.1: (a) Image of a real scale building in Dresden and (b) 2D schematic of duct geometries.

made above in the Methodology section of this paper, result oriented performance in terms of wind energy yield was compared from each design as the measure of aerodynamic performance. Each model has an exterior of simple rectangular shape with a dimension of $0.2m\ \times$ $0.15m\ \times 0.125m$. Model-1 and Model-3 [see Fig.2] has a circular and rectangular shape with the same cross sectional area of $3.02\ \times\ 10^{-3}m^2$. This is constant along the whole length of the duct. Model-2 and Model-4 has bigger cross sectional area of $7.854\ \times\ 10^{-3}m^2$ and $8.1\ \times\ 10^{-3}m^2$ both at inlet and outlet respectively. Location of the model in the test section is represented through a schematic in Fig.3:(a).



(a)Model-1 (b)Model-2 (c)Model-3 (d)Model-4

Fig.2: 3D Schematic of the four duct models [see Hasanuzzaman 2015].

Flow visualization with laser light sheet and particles have provided a good insight of the flow features such as Aerodynamic Roughness Length (Z_0), Boundary layer thickness (δ), flow separation points (for bluff body measurement, it is usually the sharp edges), location of transition points between laminar to turbulent region and level of turbulence (where the flow is effected by the model). Schematic of the perpendicular laser plane at the center of the model is graphically presented by Fig.3:(a). Flow visualization photographs presented in this paper taken at a Reynolds number of 9.4×10^4. LDA measurement location at the inlet and outlet for all models are shown in Fig.3:(b). Finally, observations based on the experimental data are discussed at the Results section of this paper.

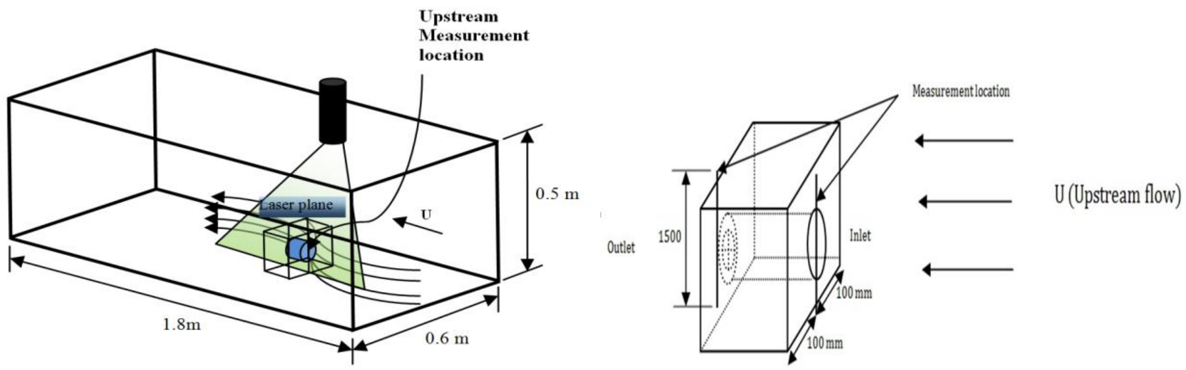


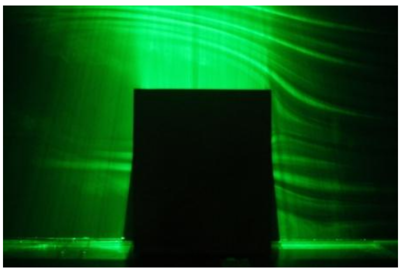
Fig.3: Principles of wind tunnel measurements, (a) Laser sheet applied from top-Flow visualization setup (b) Positions used at LDA measurements.

Flow Visualization

(a)Model-0

(b)Model-1

(c)Model-2



(d)Model-3

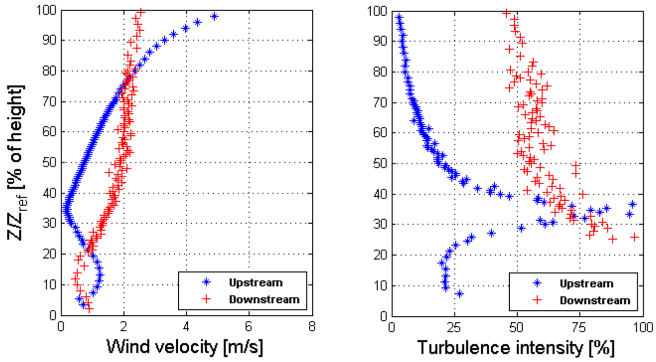
(e)Model-4

Fig.4: Flow visualization images for five different models at $Re \approx 9.4 \times 10^4$.[see Hasanuzzaman 2015]

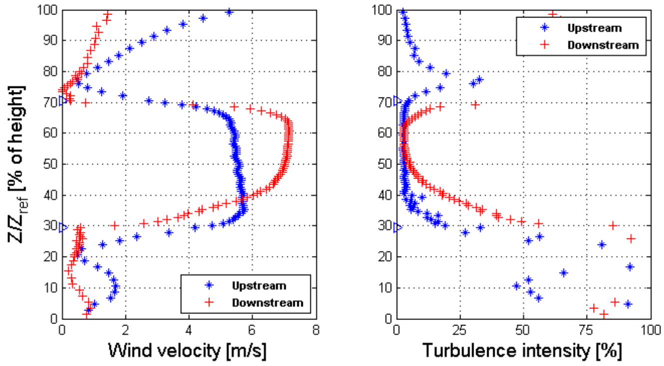
From the corresponding photographs obtained from flow visualization, it is visible that a distinct volume of the incoming flow is sucked into the ducts due the obstacle made by the building wall [see Fig.4: (b),(c),(d) and (e)]. To identify the difference between the models with duct and model without duct, a model of regular building with the same exterior dimension was also investigated as Model-0. This bluff body is denoted as Model-0 in this paper. Flow visualization image of the Model-0 is presented in Fig4. Flow separation occurs at the upstream sharp edge, and re-circulating zone is present at the upstream region near surface. However, these images have shown qualitative analysis of the flow around building models.

LDA Measurements

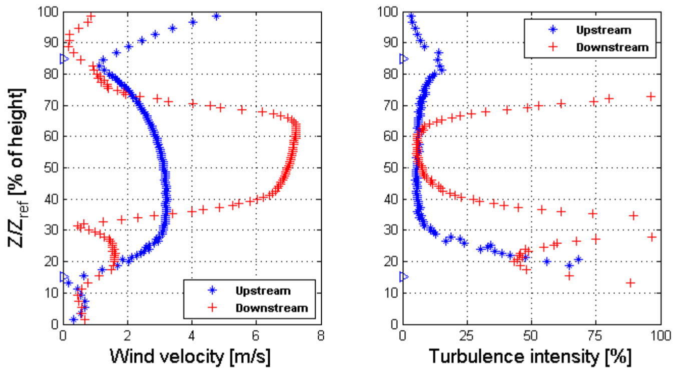
LDA measurement at the location shown in Fig.3:(b) provide a quantitative analysis of the flow velocity at the upstream inlet and downstream outlet of the duct. From the particles passing through LDA fringe, a Gaussian distribution was used to produce time averaged mean of the flow velocity at the specific location. Based on the data obtained from two component velocity measurement, magnitude of the mean velocity was calculated. Turbulence present in the flow was calculated using standard deviation. Both mean velocity and turbulence intensity are plotted against the vertical height of the model from surface (Fig.5). However, quantification of the kinetic energy present in the flow from each duct geometry is calculated from the duct locations [see Fig.1:(b)]. Average mean velocity present at the inlet and outlet of the duct was converted into the available kinetic energy.



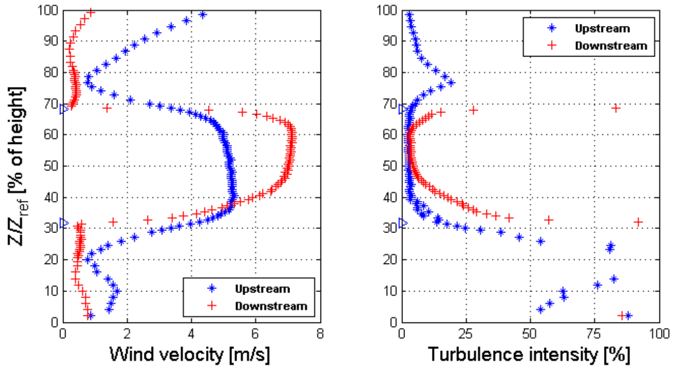
(a) Model-0



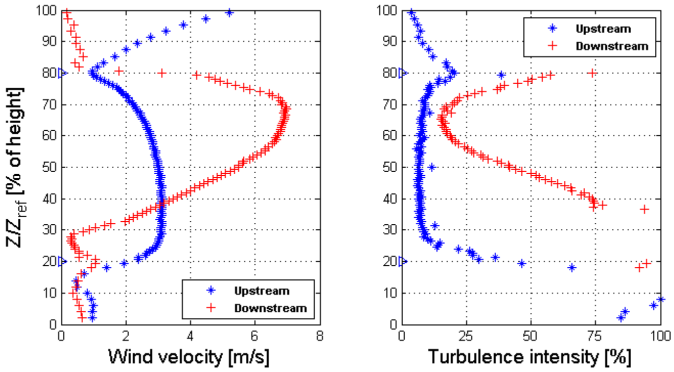
(b) Model-1



(c) Model-2



(d) Model-3



(e) Model-4

Fig.5: Wind velocity (Left) and turbulence intensity (right) measured using LDA for a regular building (b-e) with four different duct geometries [see Hasanuzzaman 2015].

Conclusion

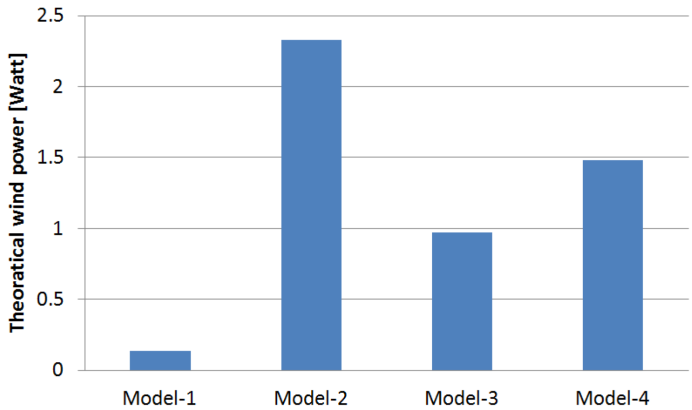


Fig.6: Graphical representation of the kinetic energy yield from different duct geometry [see Hasanuzzaman 2015].

Using the difference between the mean velocities of the wind flow at ducts, we obtain the possible kinetic energy yield [see Fig.6]. Model-2 has the highest wind power yield from the experimental data among all models. However, Model-4 has 67.76% higher intake area then Model-3 but only 34.48% higher energy yield then Model-3. Model-1 and Model-3, both these models have almost same duct area where as the energy yield from Model-3 is 7.18 times higher than that of the energy yield from Model-1 duct.

Literature

Moomaw, W., F. Yamba, M. Kamimoto, L. Maurice, J. Nyboer, K. Urama, T. Weir, 2011: “Introduction in IPCC special report on renewable energy sources and climate change mitigation” [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C.von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p-04.

Mazur, K., 2014: “Nuclear power in Germany”, www.world-nuclear.org, URL: http://www.world-nuclear.org/info/Country-Profiles/Countries-G-N/Germany/, (21.12.2014).

Ender, C., 2014: “Wind energy use in Germany-Status 31.12.2013”, in: DEWI MAGAZIN, Number-44,37.

Dondi, P., Bayoumi, D., Haederli, C., Julian, D., Suter, M., 2002: “Network integration of distributed power generation”, Journal of Power Sources 106, pp. 1–9.

“Energy consumption from buildings”, 2014, German federal ministry for economic affairs and energy, URL:http://www.efficiency-from-germany.info/ENEFF/Navigation/EN/Energyefficiency/energyefficiency.html, (21.12.2014).

Martens, S., 2006: “Wind energy in built environment”, Multi-science, UK, ISBN 0906522358. p 28-60

Plate, E.J, Cermak J.E., 1963: “Micro-meteorological Wind Tunnel Facilities: Description and Characteristics”, Final Report, Contract No. DA-36-039-SC-80371 with U.S. Army Electronic Research and Development Activity, Fort Huachuca, Arizona, February 1963, CER63EJP-JEC9, Characteristics of wind velocity in the lower layer of the atmosphere near the ground: strong winds (Neutral atmosphere); ESDU,1972.

Hasanuzzaman, G., 2015: “Experimental investigation and CFD analysis of wind energy estimation considering building integrated ducts”, Unpublished master thesis, Brandenburg Technical University, Cottbus-Senftenberg, Germany.