SIGNIFICANCE OF ENVIRONMENTAL WIND TUNNEL (EWT) TECHNIQUE IN AIR POLLUTION STUDIES: THE INDIAN CONTEXT

Sharma, N[1], Chaudhry, K.K[2] and Chalapati Rao, C.V [3]

[1]Scientist, Central Road Research Institute, Mathura Road, New Delhi (India)

[2] Professor, Deptt. of Applied Mechanics, Indian Institute of Technology, New Delhi (India)

[3]Deputy Director, National Environmental Engineering Research Institute, Nagpur (India)

Abstract The Environmental Wind Tunnel (EWT) technique has emerged as one of the most widely used technique to carry out a wide rage of air pollution studies. In the last four decades, the EWT technique, also know as fluid modelling, have shown promising results in analysing complex fluid dynamical problems that are presently intractable through analytical/ numerical technique. In the EWT, the emission conditions, different meteorological situations, terrain and topographical features can be changed at will and useful data translatable to the real life situations can be obtained. Infact the EWT technique now a days is being used extensively to bridge the gap between the actual field conditions and various mathematical assumptions in conjunction with numerical modelling. In India, an EWT has been recently constructed and put operational at the Indian Institute of Technology (IIT) Delhi. This facility is first of its kind in whole of South Asia. The nearest in the east is in Japan and that in the west is in Europe and USA. It is expected that with the construction of first EWT in India, an excellent and world class facility has been made available to the Indian scientists and researchers. Infact, the study of various air pollution problems through EWT technique is vital in Indian context as more and more metropolitan cities are getting chocked with various types of air pollutants and even cities like Delhi and Mumbai are getting distinction of being the most polluted cities of the world. The present paper briefly describes the salient feature of EWT facility developed at IIT, Delhi along with the experimental results of the dispersion studies carried out for simulated point and line sources.

Keywords- Air Pollution, Environmental Wind Tunnel, Similarity Considerations, Atmospheric boundary layer.

INTRODUCTION

"A well designed and carefully executed fluid modelling study will yield valid and useful information – informations that can be applied to real environmental problems with just as much and generally more credibility than any current mathematical models)." (Snyder, 1981)

Dispersion of pollutants released to the atmosphere depends or meteorological parameters like wind speed and atmospheric stability as decided by adiabatic and environmental lapse rate in the loewer atmosphere above the ground, site parameters like terrain roughness and topography, source parameters like height of release, temperature and velocity of effluent gases etc. Although, results obtained from the field experiments widen the limits of applicability, a series of experiments have to be conducted under different atmospheric conditions. Also, it is impossible to vary systematically, Mathematical models, both theoretical and empirical, have been extensively used for air pollution estimates. Inspite of tremendous advance in the computer capabilities and numerical techniques, mathematical models still require several simplifications unrealistic assumption, such as those of homogeneity of terrain and uniform horizontal distribution of meteorological parameters etc. The fundamental fluid dynamical processes involved in the diffusion and dilution processes are quite complex and are still not very well understood, as a result, predicted values rarely represent actual values obtained in the field experiments. Although, results obtained from field experiments are direct, effective and useful but a large number of experiments have to be conducted for different kinds of terrain, different types of sources, various source heights and also during different meteorological conditions. They are extremely expensive and time consuming. Moreover, the results always depict the influence of local topography (Synder, 1979).Hence, to

[1]E-mail: niraj@cscrri.ren.nic.in

meteorological situations, terrain and topographical features can be changed at will and useful data transferable to real life situation can be obtained for a wide range of air pollution problems. (Cermark, 1989).

APPLICATIONS OF EWT TO AIR POLLUTION PROBLEMS

Environmental wind tunnels are routinely used to carry out various types of air pollution studies, which were earlier not possible and/ or convenient through conventional methods. Infact, despite of tremendous increase in computational capabilities and scientific and technical know-how, the atmospheric dispersion phenomena is still not well understood and it is still not possible to represent and convert various dispersion and dilution phenomenon taking place in the atmosphere, into mathematical equations. Recently, efforts are being made throughout the world to use the EWT technique to help in understanding dispersion phenomenon in the atmosphere and also to bridge the gap between ground realities and mathematical assumptions. There are wide range of air pollution problems in which EWT's have been successfully used to find out their solution. Some typical applications for which wind tunnels are routinely used are (Sharma and Chaudhry, 2000)

(i) Dispersion studies on pollutants and toxic gases from stacks, automobiles etc. in complex terrain.
(ii) Testing and validating of atmospheric dispersion models under variety of atmospheric conditions.
(iii) Studies on desperation of heavier or lighter than air gases from accidental releases.
(iv) Studies on wind pick up of contaminated soils.
(v) Simulation of heat island and land-sea breezes and thier effects on dispersion of pollutants.
(vi) Study on two phase flows of pollutants.
(vii) Studies on the effect of pollutants on the plant life under dynamic environmental conditions for various geographical regions.
(viii)Specific case studies e.g. effect of a large sources of pollution, impact on monuments etc.
(ix) Generation of data on failure rates due to extreme environmental stresses for impact and risk assessment models.
(x) With proper scaling and compatible boundary layer formation, problems relating to gas flaring can also be simulated.

The summary of various air pollution dispersion studies alongwith the results by using EWT technique has been reported by Sharma and Chaudhry (2000). These studies have shown that it is possible to accurately simulate the atmospheric/ environmental, emission topographical and terrain conditions in the EWT and same can be used effectively for studies on air pollutants dispersion. Infact, wind tunnel studies under different type of emission, meteorological and terrain conditions are very vital in Indian context, as more and more Indian cities are getting chocked with severe air pollution problems, More so over, the mathematical models are not suitable for calculating pollutant concentrations in building wakes, in hill-valley complexes, from very high sources, with in the domain of urban heat island etc. (Snyder, 1979). In the past four decades the Environmental Wind Tunnel (EWT) simulation studies have shown great potential of solving the complex fluid dynamical problems. In the laboratory, the emission conditionsresulting from different types of industrial and vehicular sources and some of these Indian cities have even acquired the dubious distinctions of being the worst polluted cities of the world.

DESPERSION STUDIES THROUGH EWT INVESTIGATIONS

A meteorological or environmental wind tunnel (EWT) differs conceptually from a conventional aerodynamic wind tunnel. Unlike the conventional aerodynamic wind tunnel, efforts are made to simulate atmospheric boundary layers deep enough so that they extend well above the modeled structure of reasonable size. Also, as compared to conventional wind tunnel, comparatively lower wind speeds are required in EWT to account for buoyancy effects in atmospheric flow, which have a dominant influence in the diffusion processes. In aeronautical engineering terminology, these EWT can be conveniently classified as ultra low speed boundary layer wind tunnel (BLWT) (Snyder, 1979). In EWT technique, a moving air stream is provided for experimental studies. Further, in this technique meteorological conditions are simulated by velocity and temperature profiles. Changes in wind velocity and wind direction are simulated by changing the speed of air and changing the orientation of the model in EWT with respect to the flow of moving air respectively.

Similarity Considerations

The success of wind tunnel in air pollution dispersion studies highly depends upon achieving proper similarity between the model and the real time processes. Strict similarly of atmospheric phenomena is generally not possible and some relaxation of the modelling requirements becomes unavoidable (Cermak, 1989; Snyder, 1989) While, there is consensus on the degree of similarity necessary for simulation of wind induced effects on the buildings, the same is lacking in the area of diffusion modelling. It is recognised that strict modelling is not practicable but there is disagreement on the degree of relaxation of scale parameters which is permissible before wind tunnel result become non-representative. Basic criteria for kinetic, dynamic and thermal similarities that can be derived by inspectional Further, the following non-dimensional parameters should be equal for both model and prototype for exact similarity.

(i) Reynolds number $Re = UL/\upsilon$

(ii) Richardson number: $Ri = (\Delta T/T)(Lg/U^2)$

(iii) Rossby number $Ro = U/L\Omega)$

(iv) Prandtl number $:Pr = \upsilon p C p/k$

In addition,the boundary conditions for similarity are:

(i) surface roughness and temperature at ground level

(ii) flow structure above the surface flow, i.e. atmospheric boundary layer (ABL)

(iii) zero pressure gradient in the direction of mean flow

(iv) upwind fetch to establish a simulated ABL in equilibrium with surface boundary conditions.

Laboratory scale limitations require use of length scales in the range of 1:100 to 1:10,000 therefore physical modelling must be treated from the viewpoint of 'approximate" similarity rather than "exact" similarity. The magnitude of prototype Reynolds numbers Re_p are several order of magnitude greater than model values Re_m; Further, model values of Ro_m are several orders of magnitude larger than Ro_p; therefore, turning of the mean wind vector withheight in response to coriolis acceleration is not required to be simulated. By incorporating heating and cooling componenents in a wind tunnel, values of Ri_m over a wide range of Ri_p values (-1 to +1) can be achieved. When air is at atmospheric pressure for both, the model and prototype, the model Pr_m is essentially equal to Pr_p.

Reynolds number independence (RNI) in fluid modeling

Ukeguchi et al (1967) and Cermak (1989) and have described the various similarly laws which are generally considered in wind tunnel for carrying out atmospheric dispersion experiments. They have also discussed the criteria under which certain parameters (i.e. Reynolds number) can be ignored without effecting wind tunnel results, thus making simulation much easier. Snyder (1981) observed that the Reynold's number is the most abused criterion in the modelling of atmospheric flows and if strict adherence to the Reynold's number similarity criteria is required, no atmospheric flows could be modelled. Cermak has emphasised the importance of what had been called "Reynold's Number Independence "(RNI)", and observed that, Reynold's number (Re) need not be matched between model and prototype if model Re is kept sufficiently large. He further observed that the "aerodynamically rough" surface inequality of Re for model and prototype is not a deterrent to achieve flow similarity provided Re exceeds a value, that depends upon the relative surface roughness (K_s/L_f). He also observed that if the R_{e*} $[(U_* K_s)/\mu]$is greater than 70, the local drag coefficient is independent of Re. Thus, strong winds can be modelled in low speed wind tunnels, using air at atmospheric pressure.

Development of Atmospheric Boundary Layer in the Wind Tunnel

The Atmospheric Boundary Layer (ABL) is defined for wind engineering purposes to be a region between the surface and gradient wind height Zg, where the mean wind speed u become maximum U (Umax.). The ABL is also referred to as Ekman Layer, the friction layer or the planetary boundary Layer, which is concerned with that portion of the atmosphere where the aerodynamic friction due to the motion of the air relative to the earth's surface is of prime importance. After extensive literature review Connihan (1975) concluded that the boundary layer depth is 600 m, practically independent of wind speed and surface roughness. Davenport specified the depth as a function of roughness length Z_0 only, varying from δ = 300m at Z_0 = .03m to δ = 600m at Z_0 =. 3m. The mean velocity profile throughout the entire depth of the boundary layer is adequetty represented by a power Law

$U/U_{max}=(Z/Z_{max})^{\alpha}$ ………………………………..*(1)*

Also, the depth of the surface layer, in which the mean velocity profile follows a logarithmic law and from which the roughness length can be calculated, is about 10% to 20% of boundary layer depth. The roughness length Zo may be derived from the mean velocity profile expressed as

$U/U_* = 1/k\ l_n (Z/Z_0)$. ………………………..(2)

Infact, laboratory simulation of adiabatic i.e. neutral atmospheric boundary layer in wind tunnel is a prerequisite to model environmental problems like dispersion of air pollutants, flow characteristics in wind energy and wind loading studies. It employs the technique of developing a thick boundary layer, naturally over a long fetch of roughness in a long wind tunnel or artificially, in short test section of the wind tunnels by means of passive devices. simulation

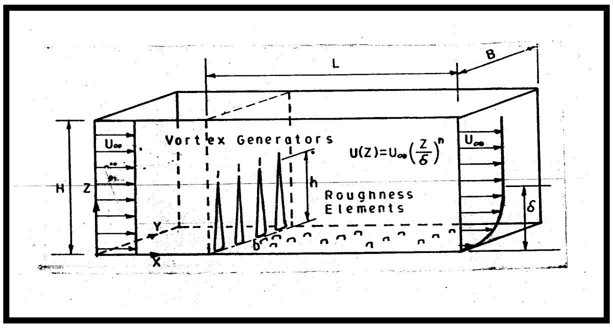

Fig. 1. Generation of a boundary layer wind profile by use of vortex generators and artificial roughness elements

methods employ the technique comprising between the two, in which natural boundary layer is allowed to develop over an intermediate length of rough wall after giving an initial start by means of barriers and mixing devices. **Fig 1.**

Armit and Counihan (1968) employed a system of passive devices like barrier wall and vortex generators to simulate the turbulent ABL of a sizeable depth (≥1m) within a relatively shorter distance in the test section of the wind tunnels. Cermak (1995) has described the various boundary layer wind tunnels (BLWT'S) that have been designed and built during the last 25 years with special capabilities for modelling the ABL and also discussed the characteristics of ABL, its features that need to be modeled and the similarity criteria to be adopted for attaining "approximate similarity" rather than "exact similarity.

Generation of Different Terrain Categories in the EWT

Air pollution studies are sensitive to the nature of the terrain, i.e., whether it is rural, urban, suburban or city centre type. Four representative terrain categories have been defined in IS code: 875 part 3 (1987) vide clause 5.3.2 which are as follows:

i) Terrain Category 1, (TC –1) i.e., Open sea with average height of obstructions being less than 1.5m (Open country type).
ii) Terrain Category 2, (TC –2) i.e., flat open country with scattered obstructions having heights between 1.5m to 10m (Suburban type)
iii) Terrain Category 3, (TC –3) i.e., Well wooded areas, shrubs, industrial areas and towns with height of obstructions upto 10m (Urban type)
iv) Terrain Category 4, (TC –4) i.e., Large city centres with obstructions above 25m

For numerical and mathematical convenience, the variation of wind velocity with height above ground level depends on the terrain category in which the particular area falls as well as the (PG) stability class of the atmospheric boundary layer and can be represented power – law variation of the mean velocity. He further reported the following values of power – law exponent 'α' which is a function of the PG class and the terrain category (Table 1).

Tracer studies and concentration measurements

A wide range of tracers can be satisfactorily used in the wind tunnel experiments. In addition to hydrocarbon traces viz. methane, ethane, butane, ethylene and sulfur hexafluoride (SF_6), the use of sulfur dioxide, carbon dioxide, smoke, helium, ammonia or combination of some of these in addition to radioactive substances, have been reported in the literature for different types of air pollution studies in wind tunnel investigations. Highly accurate and reliable flame ionization detectors (FID's) are available for quantitative measurements of pollutant concentrations, downwind from a source in

PG Stability Class	**TC –1**	**TC –2**	**TC –3**	**TC –4**
A (Extremely unstable)	0.05	0.08	0.17	0.27
B (Moderately unstable)	0.06	0.09	0.17	0.28
C (Slightly unstable)	0.06	0.11	0.20	0.31
D (Neutral)	0.12	0.16	0.27	0.37
E (Slightly stable)	0.34	0.32	0.38	0.47
F (Moderately stable)	0.53	0.54	0.61	0.69

Table-1: Power law exponent α as a function of PG stability class and terrain category (Irwin, 1979)

wind tunnel experiments, when hydrocarbons are used as tracers. Titanium hydrochloride and oil smoke are the visible tracers generally used in the wind tunnel experiments. The use of these visible tracers help in saving a lot of time and energy by visualizing the area of impact of plume by narrowing the search zone which otherwise would have required a lot of time to find out the impacted zone. This technique is most useful when wind tunnel experiments are conducted to find out concentration profiles over and around the hills, complex terrains or in the building wakes.

IMPORTANCE AND RELEVANCE OF EWT EXPERIMENTS IN INDIA

Research in this area of air pollution is being carried out mainly at NEERI Nagpur, CRRI New Delhi., Indian Institute of Technology (IIT's) and in some other Indian universities. Some of these studies are theoretical i.e., they address analytical closed form solutions or numerical solution of the governing equations with initial and boundary conditions. Whereas, some experimental studied are of the nature of air sampling surveys or Environmental Impact Analysis (EIA) using Guassian models. (Chaudhry, 1995)Currently, several EWTs exists worldwide for investigating practical problems of diffusion. Some notable EWTs in the West are at Colarodo State University (USA), University of

Surrey (UK), Central de Lyon, Ecole Polytechnique Federale de Lausanne, Suisse (France) and University of Karlsruhe and Hamburg (Germany) etc. Further, in the East, EWTs are at places like Monash University (Australia) and National Institute for Environmental Studies and Mitsubishi Heavy Industries Limited (Japan). These and others, throughout the world, mostly in technologically advanced and industrialized countries, have been in operation for R&D studies for a variety of environmental problems.

Although, in India, wind tunnel facilities are available at various IIT's. Indian Institute of Science (IISc), Baangalore, University of Roorkee, Structural Engineering Research centres (SERC) Ghaziabad and Madras, National Aeronautics Limited (NAL) Bangalore, Hindustan Aeronaticals Limited (HAL), Bangalore and Indian Space Research Organization (ISRO), Tiruvananthapuram, but their field of application is confined to the area of wind effects on structures for both aeronautical and non-aeronautical applications only (Arora, 1995; Rao 1995). In India, earlier, there was no experimental facility to physically simulate the environmental conditions, using wind tunnel experiments. Further, the fluid modelling aspects of the pollutants dispersion problems have not been taken up seriously so far and the work reported in this area of research in the country is quite scanty.

WIND TUNNEL SIMULATION FACILITY AT IIT, DELHI

IIT, Delhi is the first in south east Asia to design and develop a new EWT, exclusively meant for air pollution dispersion studies (Chaudhry, 1998). It is an open circuit, low speed and suction type tunnel having a 2m × 2m cross section, with the boundary layer development cum test section of 16m length. The construction features and other details are shown in **Fig. 2.** The facility is also provided with flow measurement device like Hot wire Anemometer (HWA) for the measurement of mean value and fluctuations in the flow field. Gas chromatograph (GC) fitted with Flame Ionization Detectors (FID's) have been provided for the analysis of hydrocarbon tracer gas concentrations. An artificially thickened boundary layer with an approximate size of 900 mm has been produced by using passive device like 6 elliptic type of vortex generators (Counihan spires) of 1m heights and an array of cubical blocks of size (30 x 30 x 30 mm) with a spacing of 75mm placed on the floors of EWT.

Experimental studies were also carried out to estimate σy and σz for class D Pasquill and Gifford (PG) stability class. Dispersion experiment in the EWT was conducted by releasing a neutrally buoyant tracer gas of 5% Acetylene in Grade I Nitrogen through Model stack. The spread parameters σ_y and σ_z which are functions of downwind distance were found out at the various locations, using the non-dimensionalised form of the Guassian equations. The results were found to be in agreement with the other research workers (Gowda, 1998). Chaudhry (1998) reported about tracer experiment carried out in the simulated ABL in the EWT at IIT Delhi to obtain ground level concentrations (GLC's) at locations corresponding to the various field-monitoring stations in the vicinity of National Fertilizers Ltd. (NFL) Vijaypur (India) stacks. The experimentally observed non-dimensionalised concentrations have been compared with those of the 95 percentile values of NOx as well as NH_3 for the winter – 1994 air quality data. A power law relation was used to convert the non – dimensinalised concentrations of field data of 8 hour averaging to 1 minute averaging time corresponding to the EWT values. The power law exponents of .3 and .02 for the NOx and NH_3 respectively gave fairly good agreement between the field and the EWT data. Gowda (1998) carried out experimental studies to find out the behavior of vertical dispersion parameter (σ_z) in the near field region of roadways under different traffic conditions and terrain features. He further observed that composition of traffic affected the values of σ_z. He observed that, for all types of heterogeneous traffic conditions as simulated in the EWT, increase in σ_z due to vehicle induces effects remained predominant over a relatively longer downwind distance from the source in comparison to homogeneous traffic conditions. Recently, efforts are being made at IIT Delhi to use EWT to calibrate various mathematical models based on Gaussian dispersion equation, which are presently being used for air pollution modelling studies in India (Sharma and Chaudhry, 2000)

LIMITATIONS OF THE EWT TECHNIQUE

Despite of several advantages over conventional techniques, the wind tunnel techniques is not always fool proof and sometime require approximations and careful interpretations, to arrive at some meaningful conclusions. Some of the limitations of the wind tunnel technique have been summerised as below:

(i) It is not always practical or sometimes even not possible to simulate all the nondimensional parameters in the wind tunnel. As a result, only more important and relevant parameters are considered ignoring the less important ones. Thus, an effort is made to obtain "approximate similarity" rather than the "exact similarity".

(ii) Wind tunnel can not simulate 'Coriolis forces" (i.e. forces arising out of the rotation of the earth). However, the "Rossby number" accounting for the rotational effect of the earth can be ignored, when length scale more than 5 km is to be simulated. [9]

(iii) Wind tunnels can't simulate wind shear i.e. turning of the wind with height. The result will be seriously affected when the dispersion from tall stack is studied in the wind tunnel.

(iv) Wind tunnels are generally extremely difficult to operate at low wind speeds (≤1m/sec), as these are designed to operate efficiently at their maximum speeds. At these low speeds, the screens and honeycombs, designed to reduce turbulence, swirl and external disturbances are completely ineffective.

(v) Constructing a reliable wind tunnel facility with sophisticated and sensitive instrumentation is very costly and needs lot of expertise. Also, the wind tunnels can be used only when they are properly calibrated and standardised.

(vi) While achieving geometrical similarity, sometimes, minute details of the prototype elements of size smaller than the roughness length are not reproduced in the model. Also, the objects of same size as the roughness length are not reproduced in the geometrical form but an equivalent roughness is established in the model, which may lead to distorted models, significantly affecting overall similarity between prototype and model and thus the obtained results.

Despite the above limitations, the wind tunnel technique has proved its usefulness in understanding and analysing various complicated fluid dynamical problems. At present, efforts are also being made to use wind tunnel data in conjunction with numerical models and field data to understand various phenomena and problems which are still not very well understood.

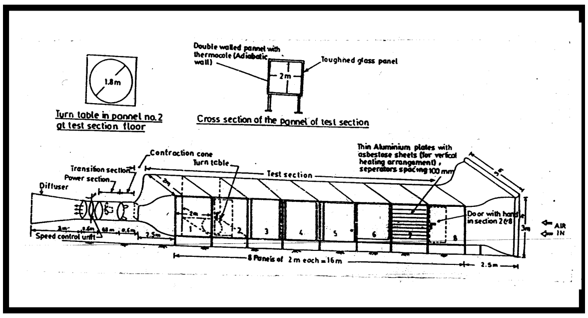

Fig 2. Layout of the 2mx2mx16m environmental wind tunnel at IIT Delhi

NOTATIONS

xyz	Cartesian Coordinates
Cp	Specific Heat at Constant Pressure
σ_y	Dispersion Coefficient in y Direction
σ_z	Dispersion Coefficient in z Direction
Pr	Prandtl Number
R_{e*}	Surface Reynolds Number
Ri	Richardsons Number
L_f	Length of Upwind Fetch
Ro	Rossby Number
μ	Dynamic Viscosity
Re	Reynolds Number
Z_o	Roughness Length
Ks	Equivalent sand Roughness Length
υ	Kinematic Viscosity of Air
U_*	Friction Velocity
L	Reference Length
T	Ambient Temperature
Ω	Angular Speed of Earth
U_{max}	Free Stream Wind Velocity
u	Mean Wind Velocity at Height Z
α	Power Law Exponent
δ	Boundary Layer Thickness
K	Von Korman Constant

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