Estimating Temporal and Seasonal Variation of Ventilation Coefficients

Ashrafi, Kh.[1*], Shafie-Pour, M. [1] and Kamalan, H. [2]

[1]Graduate Faculty of Environment, University of Tehran, P.O.Box 14155-6135, Tehran, Iran

[2] Civil Faculty, K.N.Toosi University of Technology, Tehran, Iran

ABSTRACT: The main objective of a research program, whose output is presented here, has been to estimate "Ventilation Coefficients", a critical parameter in determining air pollution concentration near the surface ground which signifies the ability for natural ventilation of an air shed in an urban or rural area. Relevant measured data from the city of Tehran has been used to calibrate and further demonstrate the validity of the mathematical model developed. Since most polluted mega cities require significant air pollution modeling activities, capable of providing relatively reliable outputs, calculating such highly important parameter is by far the most important outcome of this research. The Ventilation Coefficients have been estimated assuming normal adiabatic lapse rates and utilizing ten-year daily atmospheric radio-sound data. Mean Maximum Mixing Depth, Wind Speed at Mean Maximum Mixing Depth, and the Ventilation Coefficients have been computed and as a result it has been noted that despite the fact that Mean Maximum Mixing Depth peaks in June and Wind Speed at Mean Maximum Mixing Depth reaches its maximum in April, this has caused the Ventilation Coefficient to remain at its peack almost constant over April-June time span. It may also be observed for an urban area such as Tehran, the Ventilation Coefficient stands maximum in spring at 22329.17 m^2/s and minimum in fall at 22329.17 m^2/s.

Key words: Ventilation, Coefficient, Ambient Atmosphere, Air Pollution, Mixing Depth, Modeling

INTRODUCTION

Air pollution is one of the most serious issues in urban areas (Motesadi *et al.,* 2008). While, the accuracy of air quality models (AQMs) depends on the correct calculation of physical and chemical variables. It is clear that the meteorological parameters supplied to AQMs may contain uncertainties which adversely affect model simulations. Meso-scale weather-forecast models are usually used to supply these meteorological parameters to AQMs. The principal meteorological variables needed for AQMs, among others, are temperature, horizontal and vertical wind components, water vapor mixing ratio, precipitation, surface flux and boundary layer depth (Pino *et al.,* 2004). The majority of these variables change rapidly in the atmospheric boundary layer (Brau and Tao, 2000). Among many climatic factors, the most important is in the dispersion, transformation and removal of air pollutants from the ambient atmosphere (Giri *et al.,* 2008; Halek *et al.,* 2008). On this basis, atmospheric boundary layer (ABL) has a significant role in AQMs. ABL controls the vertical extension, concentration and transformation of atmospheric pollution to some extent. The vertical mixing of atmospheric pollutants are strongly influenced by ABL, which acts as an interface between the more polluted region near the earth's surface and the relatively cleaner free atmosphere above (Krishnan and Kunhikrishnan, 2004).

On the other hand, Maximum Mixing Depth, that is the height in which pollutant can have a

*Corresponding author E-mail: khashrafi@ut.ac.ir

vertical movement up to and partially into inversion layer, has a direct relation with ABL (Deardorff, 1980). In other words, mixing depth is a critical parameter in determining air pollution concentrations near the ground which represents the depth through which pollutants are vigorously mixed (Berman *et al.,* 1999). This parameter is highly important because using such data and the wind speed profiles, the corresponding "Ventilation Coefficient" (VC) can be calculated. In fact, ventilation coefficient is the power of pollution discharge or ventilation from captured-air beyond the inversion layer (Cheremisinoff, 2002). In this context some consider the importance of VC as a non-separatable annex of air pollution potential (Krishnan and Kunhikrishnan, 2004).

There are different methods to estimate the mean maximum mixing depth (MMMD) such as Lidar observation, numerical experiment (MM5), simple diagnostic model (AERMET), Profiler-Derived CBL Height, and ultra high frequency (UHF) wind profiler, and lapse adiabatic line (Pino *et al.,* 2004; Matthew *et al.,* 2007) and (Krishnan and Kunhikrishnan, 2004; Arya, 1994). A Lidar observation, which is among the most expensive methods, is continuously monitored by means of radiosondes observations usually twice a day (Pino *et al.,* 2004). A successful study has been conducted to investigate how the non-hydrostatic meso-scale model MM5 is to reproduce a boundary layer height evolution in an urban area in Barcelona (Pino *et al.,* 2004). Recent developments in radars such as development of UHF wind profilers, made it possible to monitor the ABL growth (Krishnan and Kunhikrishnan, 2004). AERMET, which has been developed by US Environmental Protection Agency (EPA), is a simple diagnostic model that incorporates routine surface observations and upper air radio-sound data to estimate the growth of the boundary layer (Matthew *et al.,* 2007). Surface observations of the 2 m dry bulb temperature, 10 m wind speed and direction, total cloud cover, and station pressure are required by AERMET. Also, the lapse rate above the morning boundary layer is needed (EPA, 2004). Observed mixing height over an urban area can be derived from the signal to noise ratio (SNR) profiles measured by two profilers with 5 beams and series of 30-min-measuements of speed and direction of wind and SNRs (White *et al.,* 1991).

There are some methods to estimate the wind speed at maximum mixing depth such as power law, Monin-Obukhov, and direct measurement. Power law method uses a measured wind velocity at a reference height and then calculates the wind velocity at a considered height by a power parameter which depends on air stability (Masters, 1996). Monin-Obukhov calculates almost all needed parameters with an acceptable accuracy; nevertheless it is more cumbersome (Monin and Obukhov, 1954; Arya, 1994). The main objective of this paper focuses on the estimation of MMMD and its corresponding VCs temporally and seasonally for urban areas such as the city of Tehran.

Capital of Iran, Tehran, with about 8 million inhabitants (ICE, 2005), when compared with WHO guidelines has a polluted air. Meteorological data (atmospheric radio-sound profiles and maximum daily temperature at ground surface) have been obtained for Mehrabad synoptic station which is located in latitude of 35:41, longitude of 51:19, and altitude of 1190.8 m. Fig.1. shows the geographic situation of Mehrabad station at a glance. Atmospheric radio-sound data of Mehrabad Station have been gathered from University of Wyoming database and maximum daily temperature at ground surface from Mehrabad station data base for a minimum period of ten years.

MATERIALS & METHODS

Since usually direct measurement data are made available through atmospheric radio-sound information, interpolation of direct measurement data may be applied to estimate wind speed at maximum mixing depth. In fact, the amount of air available to dilute pollutants is related to the wind speed and to the extent to which emissions can rise into the atmosphere. On this basis atmospheric temperature profile is highly important (Arya, 1994). If a parcel of air at ground level is warmed by convection on a sunny day, its buoyancy will make it rise. As the parcel moves upward it cools adiabatically at about $1^{o}C/100$ m. If its temperature is warmer than that of the surrounding air, it will continue to rise; if it is less, it will fall. At some point, if its temperature becomes equal to that of the surrounding air, it will stop moving. By having
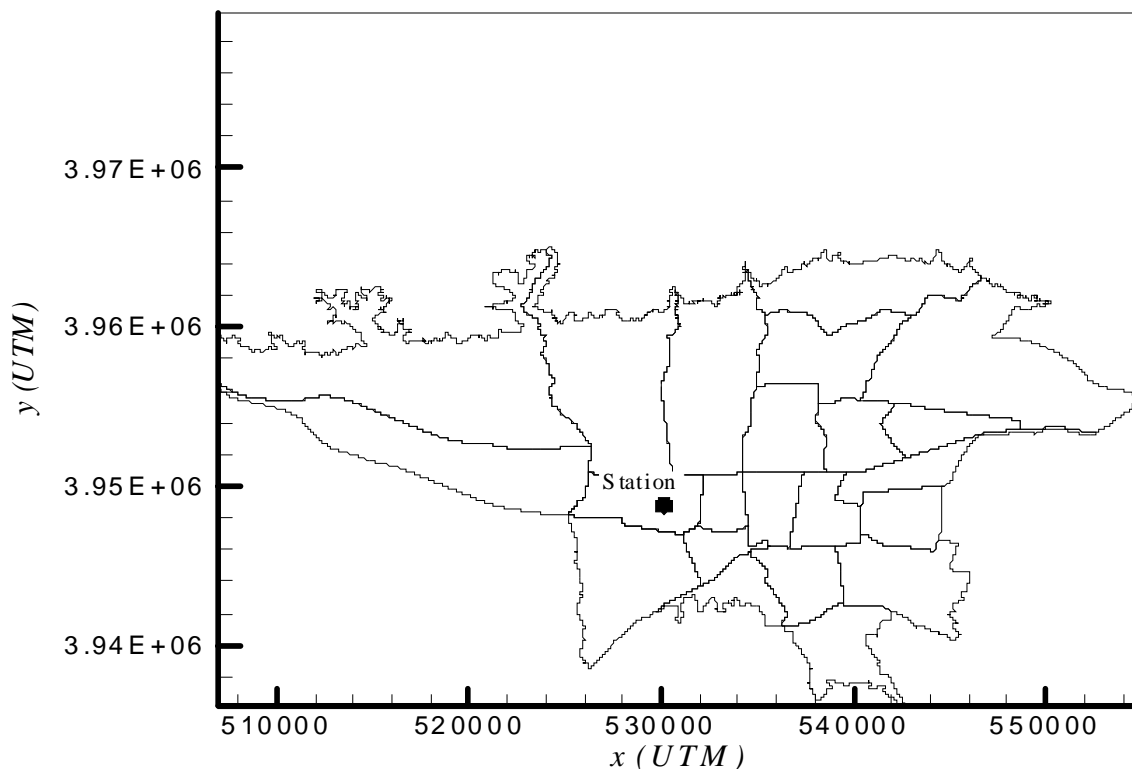
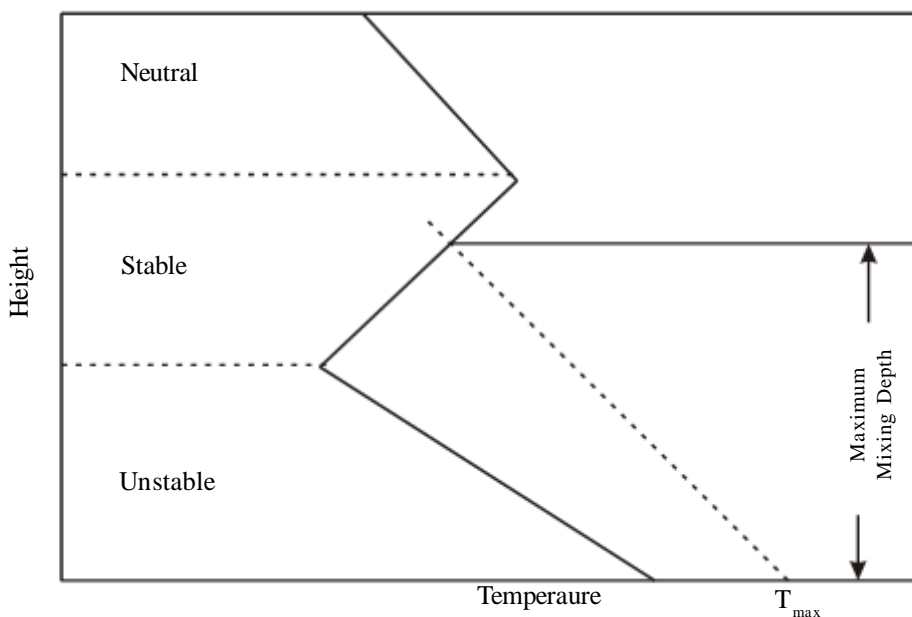**Fig. 1. Geographic situation of Mehrabad synoptic station in Tehran**

Fig. 2. Procedure of obtaining maximum mixing depth (Shafie-Pour and Khamsei, 2008)

temperature profile, determination of the elevation to which the parcel crosses the profile is achievable (Shafie-Pour and Khamsei, 2008). The procedure, in this study, to reach this point which is called maximum mixing depth is as follows: (1) actual measured temperature profile in the early morning (morning temperature radio-sound data at 00:00 GMT) is drawn for each day, (2) a line is drawn for each day from maximum day time ground level temperature data with the slop of adiabatic laps rate, and (3) the altitude where the line mentioned in item 2 intersects the line drawn in item 1 is maximum mixing depth. Fig. 2 shows this procedure schematically.Since radio-sound

information contains wind speed in different elevations, wind speed at maximum mixing depth level is calculated by interpolation. On this basis, wind speed at different levels up to the maximum mixing depth level is made available. Thus, ventilation coefficient is calculated for each day by using equation (1):

$$VC = \int_{0}^{maximum\ mixing\ depth} U(z)\ dz \qquad (1)$$

Based on available numerical models knowledge, Equation 1 can be discretted as equation (2):

$$VC = \sum_{i=1}^{n} U_i(z_i) * \Delta z_i \qquad (2)$$

where VC is ventilation coefficient (m^2/s), $U_i(z_i)$ is wind velocity at ith level (m/s), z_i is ith level (m), and n is number of available data (level and wind speed) up to maximum mixing depth level.

Above mentioned calculations have been applied for a 10-years data from 1996 to 2005. Then average value of each parameter (maximum mixing depth, wind speed at maximum mixing depth level, and ventilation coefficient) has been calculated for each month based on available data during 10 years. Also, average value of mentioned parameters has been calculated seasonally using weighted averaging.

RESULTS & DISCUSSION

The procedure of calculations has been defined in pervious section. As an example, calculations of Jan. 1st 2005 in Mehrabad Station in Tehran, is presented in Table 1. It should be noted that during the 10 years period, there are some data gaps. Data for Aug. 2002, March 2001, Nov. 1998, Nov. 1997, and Jan. up to May 1996 are not available. Also there are some days that radio-sound information is not reliable or is not available. The second column in Table 2 shows the number of days for which calculations have been done (in each month during the period). Monthly values of MMMD, wind speeds at MMMD level, and ventilation coefficients are shown in the next columns of Table 2. Also, the seasonal parameters variations over 10-year period are shown in Table 3. at a glance for Tehran.

It is noticeable that VC is the ability of self air pollution reduction (purification) in an urban or rural area. Higher VC results in more clean air. Thus, this vital parameter can be considered as an index in urban air pollution plans, programs, and modeling activities. As an important example, the traffic situation has its own trend during the year, but air quality varies day to day. The reason is daily (and temporal) changes in natural meteorological parameters such as temperature, wind speeds and as a result VC.

Maximum values of VC and MMMD have been calculated for June, while maximum wind velocity at MMMD level is in April. It confirms that MMMD is a highly important parameter. As it is shown in Fig. 3. MMMD has a gradual rise from Jan. to May. Then it is almost steady from May to Aug. with a drop in July. MMMD has a gradual fall from July to Dec. Since the wind velocity is another factor in determining VC, Fig. 4. shows such changes in the same synoptic station in Tehran. Fig. 5. represents that the trend of the VC variation is almost similar to MMMD.

Since values of the parameters are almost in the same range, they are illustrated seasonally in Figs 6, 7, and 8. Spring and summer have almost the same value for MMMD. It is similar for fall and winter with a lower value than that for spring. On this basis, VC values for spring and summer are higher than those for fall and winter. Ventilation coefficients for winter, spring, summer, and fall stand at 10114.83, 22329.17, 16880.09, and 7901.40 m^2/s; respectively.

CONCLUSION

Since VC is an invaluable parameter in air pollution modeling, planning, and decision making, it has been calculated for the first time for an urban area, such as Tehran over a 10-year period in this study. As daily early morning radio-sound data and daily maximum temperature at ground level data are available from 1996 untill 2005 for Tehran, adiabatic lapse method has been chosen to estimate maximum mixing depth. Interpolation method has been applied to calculate wind speeds at maximum mixing depth levels. Finally daily VC has been calculated utilizing summations of multiplication of wind velocity by height in different levels up to maximum mixing depth. Monthly and

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Table 1. Maximum mixing depth calculations for Jan. 1st 2005

H (m)	T (°C)	U_i (m/s)	i	z_i	T_{ady} (°C)	T (°C) at inter sec tion	MMD	U at MMD	$U_i \times \Delta z_i$	VC
146										
822										
1191	5.4	0	0	0	16.2				0	
1238	7.4	0.51	1	47	15.73				24.18	
1399	9.8	3.09	2	208	14.12				496.95	
1525	9.4	4.63	3	334	12.86				583.38	
1613	9.4	5.66	4	422	11.98	10.49	570.54	7.27	1079.54	2184.05
1803	10.8	7.72	5	612	10.08					
1873	10.2	8.23	6	682	9.38					
2403	5.9	11.32	7	1212	4.08					
2980	1.2	12.86	8	1789	-1.69					
3037	1	12.86	9	1846	-2.26					
3117	0.8	13.38	10	1926	-3.06					
3480	-1.1	15.95	11	2289	-6.69					
3857	-4.5	18.52	12	2666	-10.46					
4508	-9.1	22.64	13	3317	-16.97					
4628	-9.7	23.66	14	3437	-18.17					

T_{max} at surface is 16.2 °C

Table 2. Monthly MMMD, wind speed at MMMD level, and VCs over 10 years

month	days	MMMD (m)	Wind speed at MMMD level (m/s)	VC (m^2/s)
Jan.	172	1251.24	6.64	6261.90
Feb.	160	1722.21	9.29	9903.44
Mar.	156	2094.77	9.48	14673.60
Apr.	174	2663.95	12.71	21324.31
May	190	3412.03	11.97	22577.83
Jun.	199	3595.78	10.42	22970.38
Jul.	232	3213.85	8.71	17301.62
Aug.	158	3357.57	6.03	20984.21
Sep.	193	2815.46	7.95	13013.51
Oct.	177	2402.12	7.58	10588.55
Nov.	131	1446.77	6.13	7196.36
Dec.	183	1059.91	6.06	5807.05

Table 3. Mean seasonal MMMD, speed at MMMD level, and VC over 10 years

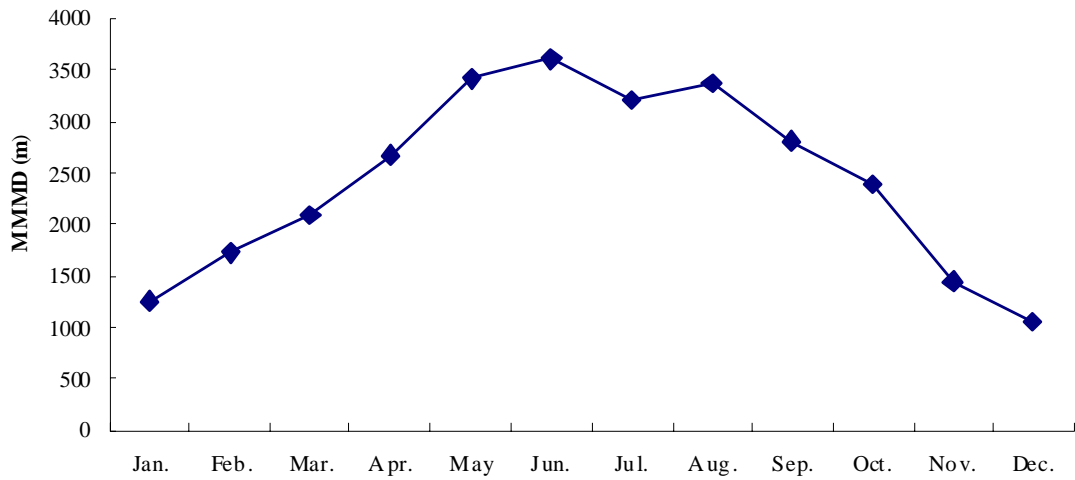| season	MMMD (m)	Wind speed at MMMD level (m/s)	VC (m^2/s)
Winter	1675.31	31.80	38332.39
Spring	3245.78	44.03	84371.08
Summer	3120.91	29.22	63781.64
Fall	1646.98	25.03	29855.54

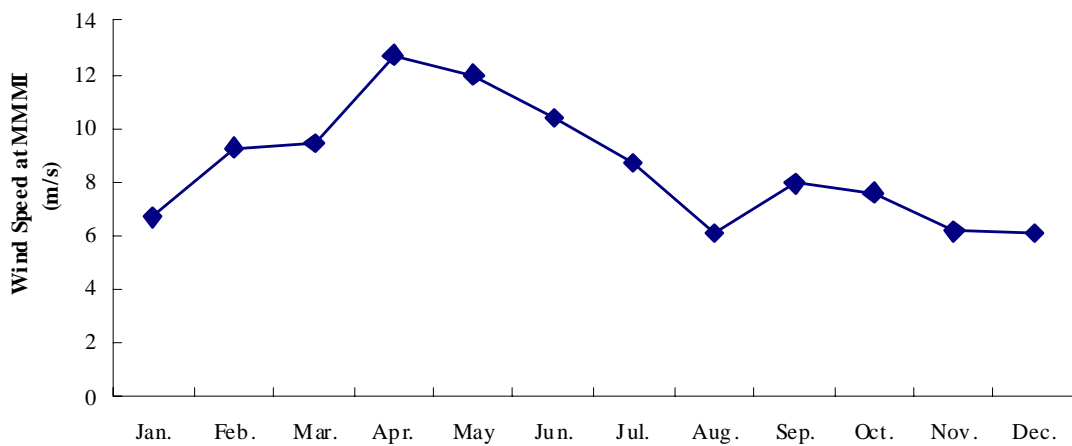**Fig. 3. Monthly MMMD in a 10-years period in Tehran**

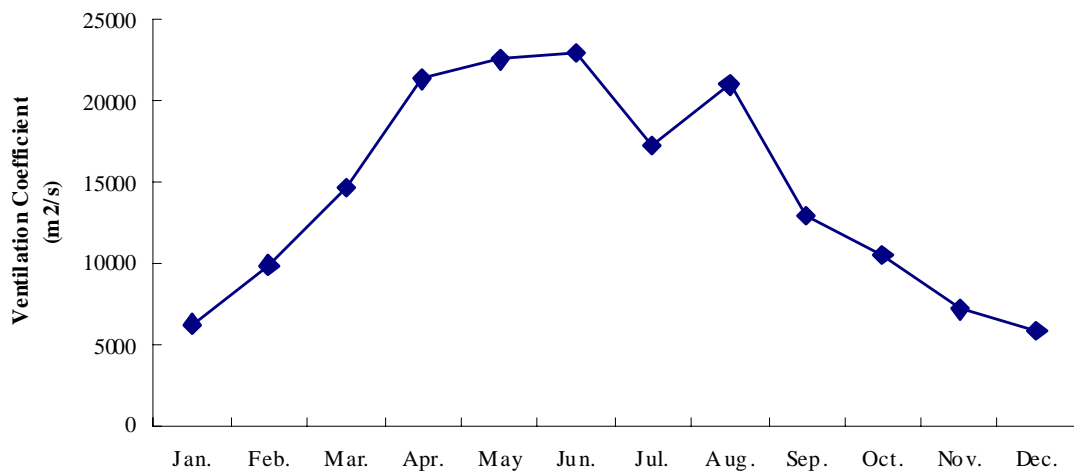**Fig. 4. Monthly wind speed at MMMD in a 10-years period in Tehran**

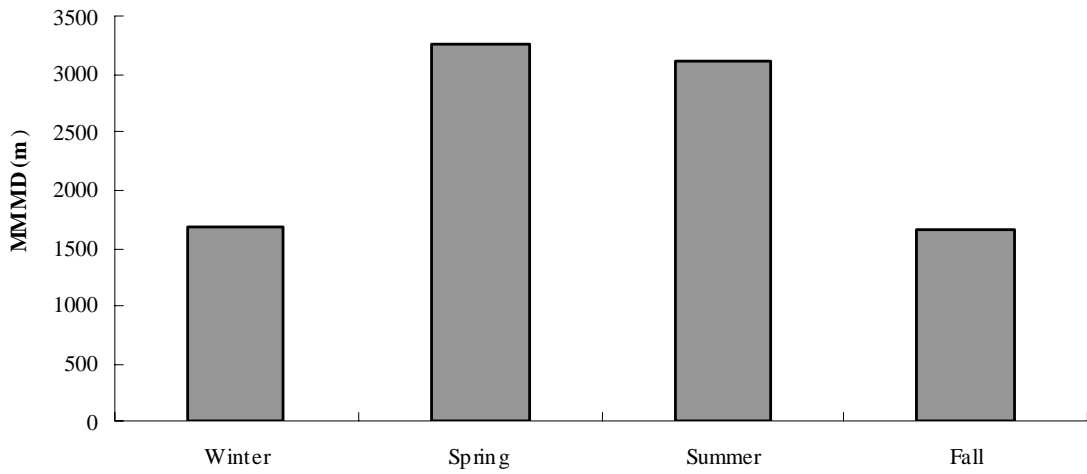**Fig. 5. Monthly VC in a 10-years period in Tehran**

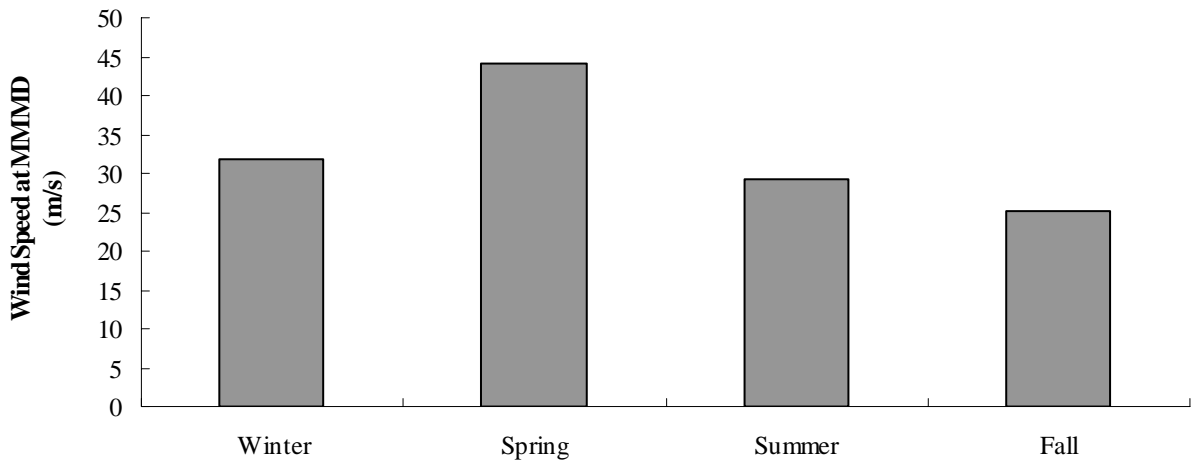**Fig. 6. Seasonal MMMD over 10-years period in Tehran**

Fig. 7. Seasonal wind speed at MMMD level over 10-years period in Tehran
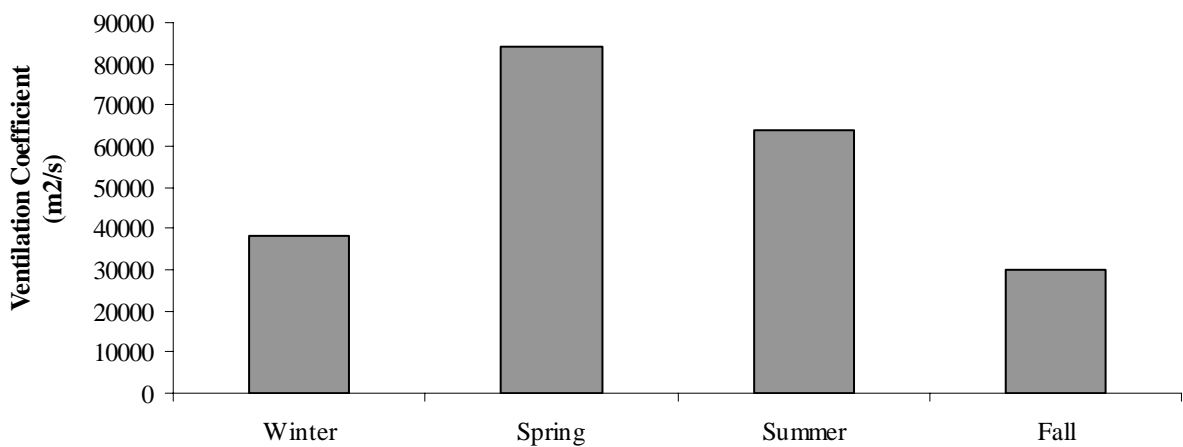

Fig. 8. Seasonal VC over 10-years period in Tehran

seasonal MMMD, wind speed at maximum mixing depth, and VC are obtained by weighted averaging. This study provides an easier and less expensive alternative method to calculate the daily and temporal VC than other methodologies such as Lidar observation, numerical experiment (MM5), simple diagnostic model (AERMET), Profiler-Derived CBL Height, and ultra high frequency (UHF) wind profiler. On this basis, it is recommendable to utilize this methodology for urban and rural areas in which VC is to be determined for air quality assessment when emphasis is on the natural ventilation ability of an extended air shed together with upper layer atmospheric radio-sound routine measurements.

ACKNOWLEDGEMENT

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