Heat Removal Under Various Wind Speeds

RIZWAN AHMED MEMON*, MUHAMMAD ASLAM UQAILI**, AND ASHFAQUE AHMED HASHMANI***

RECEIVED ON 15.12.2010 ACCEPTED ON 22.03.2011

ABSTRACT

This paper investigated the impact of velocity variation in wide streets. The building AR (Aspect Ratio) (Street-canyon-width-to-building-height i.e. W/H) has been calculated by varying the width of street canyon. The k-ε turbulence model was applied to ideal street canyons of aspect ratio 0.5, 0.75 and 1.0 while the wind speed was varied from 0.5 to 4.0 m/s. The street canyon aspect ratio 1.0 was obtained by increasing the width of the street two times (i.e. W=1) as much as for AR0.5 (i.e. W=0.5). However, different results obtained from AR1 were compared with AR0.5 to analyze the impact of wide streets. Results show that the temperatures reduce with an increase in ambient wind speed. However, the impact of ambient wind speed was comparatively higher in narrow street canyons since temperature reduced by over 1.4 K with an increase of 3.5 m/s in ambient wind speed. On the other hand, in the case of AR1.0 the area weighted average temperature reduced by 1.3 K with an increase of 3.5 m/s in ambient wind speed. It is found that removing heat from narrower street canyons is comparatively difficult. Results show that the temperatures within the target street canyon of AR0.5 with ambient wind speed of 0.5 m/s were around 0.71 K higher than that in AR1.

Key Words: **Velocity Variation, Wide Streets, Narrow Streets, Area-Weighted Temperature.**

1. INTRODUCTION

It is reported that the ambient wind speed affects the heating within the street canyon [1]. However, there is no agreement on the quantification of this influence and there has been little research in this regard [2-3]. The heat generated within the canyon could cause heating or urban heat island, as conventionally known, that in turn could seriously affect thermal comfort and increases financial losses [2,4-11]. The impacts of urban heating requires an especial attention in an area like Pakistan where an estimated 80% energy could be saved using proper thermal comfort efforts [12]. There have been many studies on evaluating the effect of urban heating; however, numerical studies in this regard are limited [7-10, 13-18]. Moreover, the reports of numerical studies on urban heating effects proved that application of CFD in particular the k-ε turbulence model is very successful in this regard [1,19-21,26]. The author of this paper noted in some of his papers that the Fluent code that incorporates the k-ε turbulence model could produce excellent simulation results for the effects of urban heating within street canyon [1,26-28]. However, the effects of ambient wind speed in wide streets were not addressed in any of the

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* Assistant Professor, Department of Mechanical Engineering, Mehran University of Engineering and Technology, Jamshoro.
** Professor, Department of Electrical Engineering, Mehran University of Engineering and Technology, Jamshoro.
*** Assistant Professor, Department of Electrical Engineering, Mehran University of Engineering and Technology, Jamshoro.

aforementioned papers although it could be very important. This paper, therefore, has been written to quantify the effects of ambient wind speed in removing the heat from wide streets. In order to address this important issue, meshes for two street canyon ARs were generated. The AR0.5 represents the narrower canyon with half width as much as for AR1. The area-weighted average results obtained for the two ARs were compared to highlight the heating difference within these ARs. The ambient wind speed value was then changed to see how it would effect the removal of heat. Finally, the TKE (Turbulence Kinetic Energy) graphs obtained from fluent were depicted and discussed to evaluate the role of turbulence in creating the heating difference in the narrow and wide streets.

2. NUMERICAL MODEL

The k-ε turbulence model was adopted in this paper to simulate the street canyon heating in wide streets. The physical model was generated for AR1.0 with rectangular structured grid and scaled to AR 0.5 and 0.75 using fluent code. The governing equations for this model cover the principles of conservation of mass, momentum and energy. The equations for aforementioned principles are given below. Since the numbers of variables are more than the number of governing equations, which is referred to as closure problem, additional equations are required to simulate any case. Additional equations for "k" and "ε" have been used as given in the RNG (Renormalization Group) theory to address the closure problem. However, the constants required to solve the governing equations have not been included in this paper. The reader is recommended to refer authors' previously published papers for detailed model or values for different constants [1, 3, 26-28].

$$\frac{\partial \overline{u_i}}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \overline{u_i}}{\partial t} + \overline{u_j}\frac{\partial \overline{u_i}}{\partial x_j} = -g_i - \frac{1}{\rho}\frac{\partial \overline{p}}{\partial \mathrm{x_i}} + \frac{\nu\partial^2 \overline{u_i}}{\partial x_j^2} - \frac{\partial(\overline{u_i' u_j'})}{\partial x_j} \tag{2}$$

$$\frac{\partial \overline{\theta}}{\partial t} + \frac{\overline{u_j}\partial \overline{\theta}}{\partial x_j} = \frac{\nu_\theta \partial^2 \overline{\theta}}{\partial x_j^2} - \frac{\partial(\overline{u_j' \theta'})}{\partial x_j} \tag{3}$$

It may be noted that equations were discretized using second order accuracy and solved in Fluent code 6.3 [29]. The boundaries wall were defined with no slip boundary condition and model top was considered as symmetry boundary. All the wall surfaces were defined with a constant temperature while the ambient air enters from the left of the canyon with a constant uniform value (Fig. 1). Notably, the k-ε turbulence model can not be adopted near the wall due to laminar nature of flow and comparatively higher velocity and temperature gradients. Subsequently, enhanced wall treatment is adopted from fluent code to solve the flow near walls; the detail of the model equations for enhanced wall treatment can be referred in authors' published work. However, a fine mesh is generated in fluent by refining the grid near boundaries to use enhanced wall treatment equations.

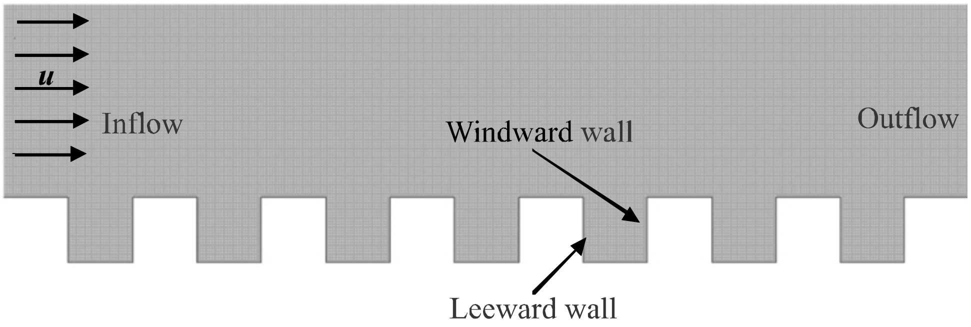


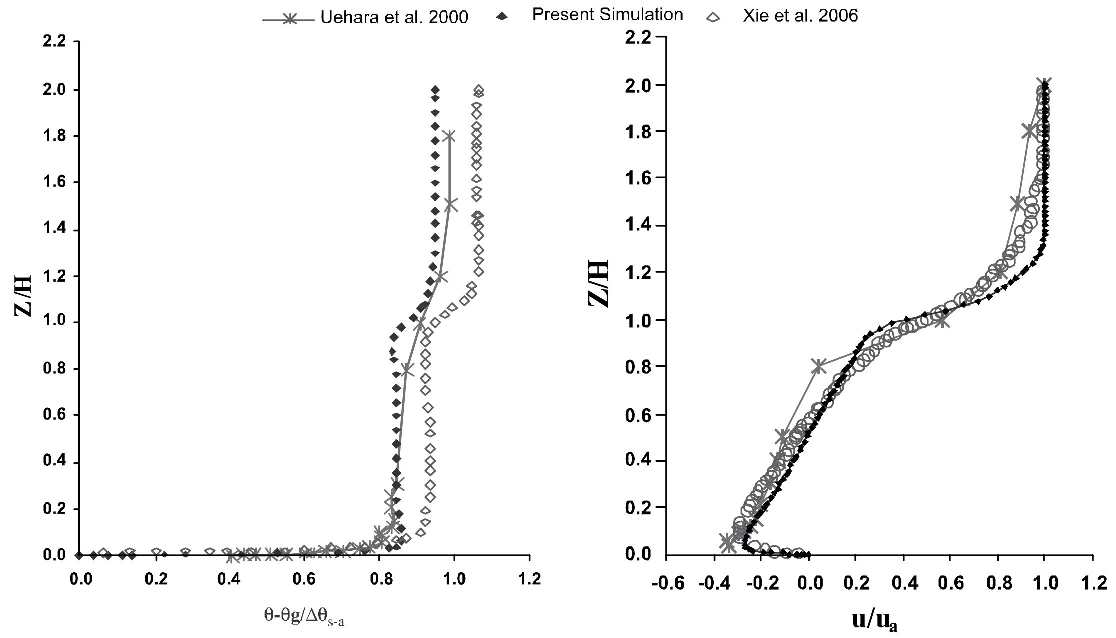
FIG. 1. COMPUTATIONAL DOMAIN OF SIMULATION MODEL

3. VALIDATION OF MODEL

The model is validated by comparing the results for normalized potential temperature $(\theta\text{-}\theta_g/\Delta\theta_{s\text{-}a})$ and horizontal velocity (u/u_a) with the results obtained from wind tunnel experiment [30]. The detail of model validation could also be found in authors' previously published papers [1, 3, 26-28]; although a short description of validation is given here as follows. In this paper, apart from the results for wind tunnel, the results obtained from Xie, et. al. [21] are also presented to get a better picture of the model (Fig. 2). It could easily be seen that the results of this model are quite close to those obtained from wind tunnel experiment in particular those for potential temperature. However, curves show that the only minor deviation is observed in the upper portion of the canyon (Z/H ~ from 0.6-1.0) in the case of potential temperature. On the other hand, the deviations in the case of horizontal velocity are higher in particular on the top of the canyon (Z/H>1.0) in the free stream flow. The detail of quantitative deviations of the results, the possible reasons of these deviations and the differences in the numerical model of this study and the wind tunnel experiment can be found in our published work [1, 3, 26-28].

4. RESULTS AND DISCUSSION

The normalized area-weighted average temperature $(\theta\text{-}\theta_a/\Delta\theta_{s\text{-}a})$ within the street canyon has been graphed versus the ambient wind speed as shown in Fig. 3. The average street canyon temperature has been calculated by taking an average of all the node point temperatures within the street canyon without including the temperature in the free stream. The average street canyon temperature is then divided with the difference between the surface and ambient air temperature for normalization. The Fig. 3 depicts the variation in the street canyon temperature with respect to wider and narrower street canyons i.e. one for AR0.5 and the other for AR1.0. Four values for ambient wind speed are used as to calculate the differences within the street canyon itself and that in the wide and narrow street canyons. It is evident that overall temperatures would be higher in the narrow street canyon (Fig. 3). Results show that the area-weighted average temperature within the target street canyon of AR0.5 when wind speed was 1, 1.5, 2, 2.5, 3 and 3.5 m/s were 1.4, 0.9, 0.7, 0.4, 0.2 and 0.1 K higher than that with ambient wind speed of 4 m/s. On the other hand, area-weighted average temperature within the target street canyon of AR1.0, when wind speed



(A) POTENTIAL TEMPERATURE (B) HORIZONTAL VELOCITY

FIG. 2. VALIDATION OF NORMALIZED HORIZONTAL VELOCITY AND POTENTIAL TEMPERATURE

was 1, 1.5, 2, 2.5, 3 and 3.5 m/s, were 1.3, 0.8, 0.6, 0.3, 0.2 and 0.08 K higher than that with ambient wind speed of 4 m/s. This result indicates that removal of heat from narrow street canyon is comparatively difficult. Evidently, temperatures within the target street canyon of AR0.5 with ambient wind speed of 0.5, 1, 1.5, 2, 2.5, 3, 3.5 and 4 m/s were around 0.71, 0.69, 0.65, 0.62, 0.55, 0.55 and 0.54 K higher than that in AR1. This clearly indicates that the temperatures within the narrow canyon would be higher and that the differences would particularly be high at low wind speeds.

It is widely known that turbulence is the main source of transport of heat and pollution. However, one of the main parameters of turbulence is TKE. In order to investigate the influence of turbulence transportation on temperature variation, the resultant TKE curves, as obtained from fluent, have been plotted in Figs. 4-5. The resultant distribution of TKE has been graphed for all the simulated cases i.e. results at ambient wind speed 1.0-4.0 m/s for both AR0.5 and AR1.0. Fig. 4(a) shows that the values for TKE reached the highest point with the windward wall while least with the leeward wall. However, the variation in the TKE value in the middle of the canyon is more evident than that with the corners and along the leeward and windward walls. The variation is especially visible as the flow changes near the leeward wall. The same figure shows that the value for TKE reaches 0.025 m^2/s^2 in the mid of the canyon. However, the highest value reaches 0.04 m^2/s^2 near the windward wall. Similarly, the highest value within the canyon reaches 0.025 m^2/s^2 near the leeward wall. A comparison with the TKE in the target street canyon with higher ambient speed (Fig. 4(b)) shows clear distinction. The value for TKE with the windward wall has been clearly increased as TKE reaches to a maximum value of 0.1 m^2/s^2. Similarly, the value for TKE within the canyon has also been increased as the value within the canyon reached to around 0.06 m^2/s^2. However, the value on the leeward side reached the minimum. Seemingly, the higher TKE generated higher turbulence that resulted in outflow of heat from within the canyon.

A comparison of the results with AR0.5 (Fig. 4(a)) and AR1.0 (Fig. 5(a)) shows that the values in AR1 could not be highest in the canyon with AR0.5. However, there is a

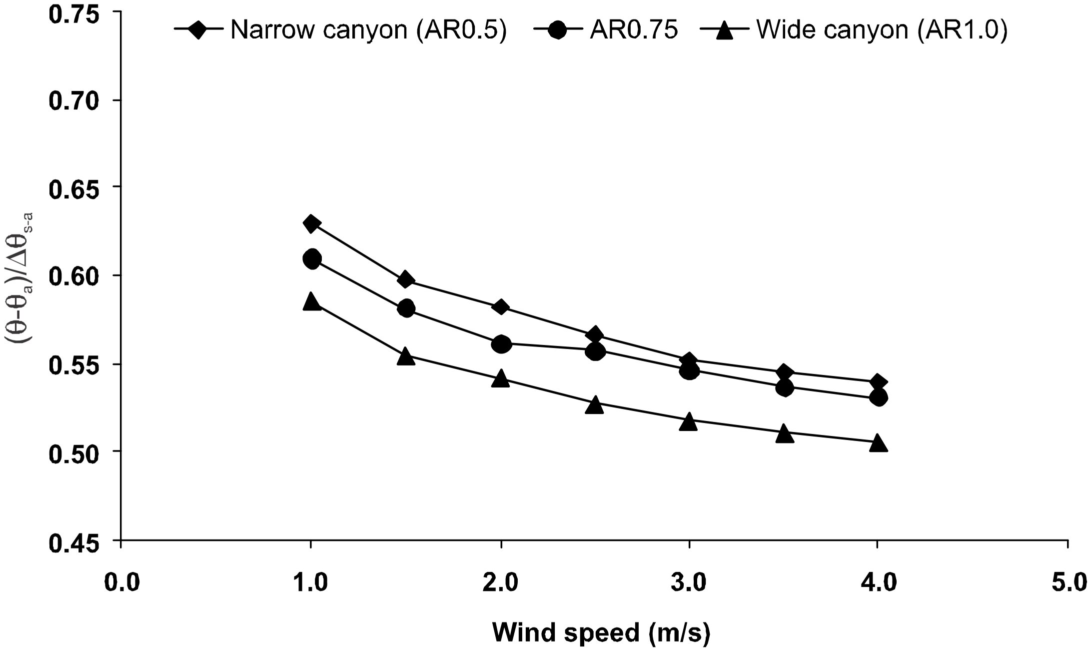
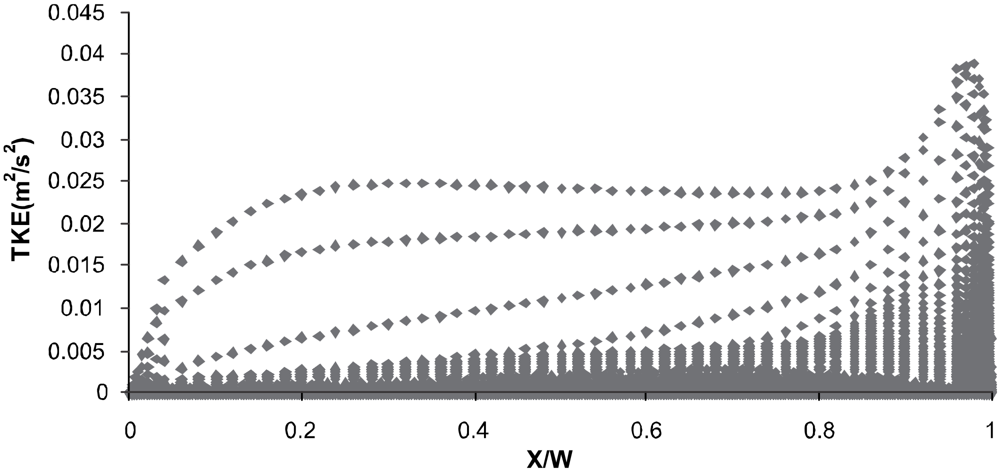


FIG. 3. NORMALIZED AVERAGE (AREA-WEIGHTED) AIR TEMPERATURE VS. WIND SPEED

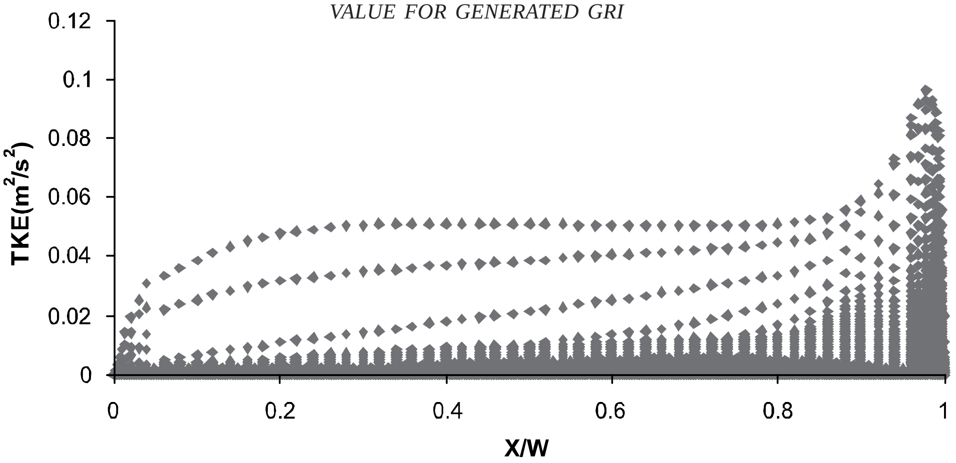
clear distinction in the nature of the curve for TKE in AR0.5 and AR1.0. There are two clear dumb-bells in TKE values connected with the ground near windward and leeward walls in almost all the simulated cases for AR1.0. Seemingly, there are sharp changes in TKE in the case of AR1 as values reached the peak and then falls back to zero at these dumb-bells and elsewhere. On the other hand, such rapid changes are not noticeable in the case of AR0.5. Notably, the values in the case of AR0.5 change gradually i.e. highest with the windward wall but the lowest with the leeward wall. Nevertheless, the changes in the TKE appeared to be very important indicator of the differences in the temperature values in AR0.5 and AR 1.0.

5. CONCLUSIONS

This paper investigated the impact of ambient wind speed on removal of heat in narrow and wide street canyons. Two different canyons were simulated by varying the width of the canyon. The width of one of the canyons (AR1.0) was kept twice as much as for the narrow canyon (AR0.5). Results show that the temperatures in the narrow canyon would be higher than that in the wide canyon. It is also found that the area-weighted average temperature in the narrow street canyon could be as high as 0.7K when the wind speed is the same in both canyons. Results also show that the TKE increases with an increase in the wind



(A). TURBULENT KINETIC ENERGY CONTOURS FOR AR 0.5 AND WIND SPEED 1.0 M/S. THE CURVES ARE GENERATED FROM TKE VALUE FOR GENERATED GRI



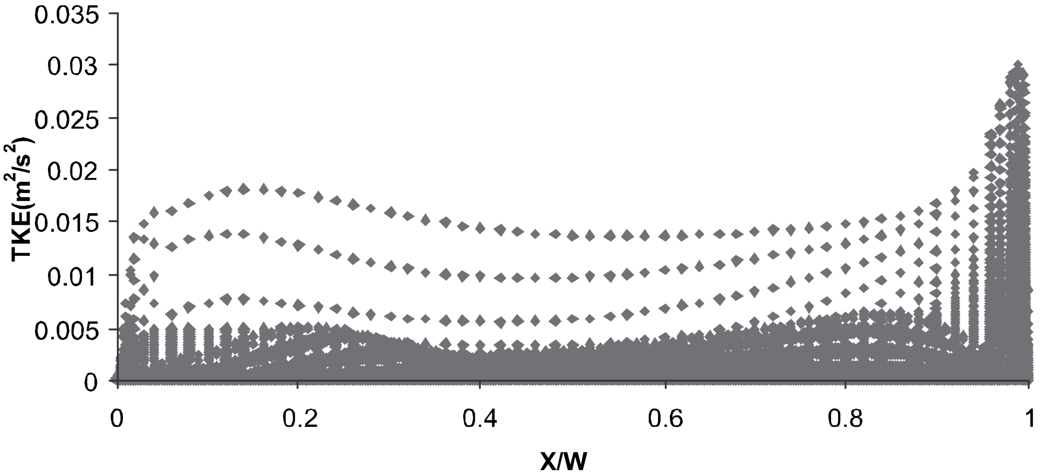
(B). TURBULENT KINETIC ENERGY CONTOURS FOR AR0.5 AND WIND SPEED 1.5 M/S. THE CURVES ARE GENERATED FROM TURBULENT KINETIC ENERGY VALUE FOR GENERATED GRID

FIG. 4. CONTOURS FOR TURBULENT KINETIC ENERGY IN NARROW STREET CANYON WITH VARYING AMBIENT WIND SPEED

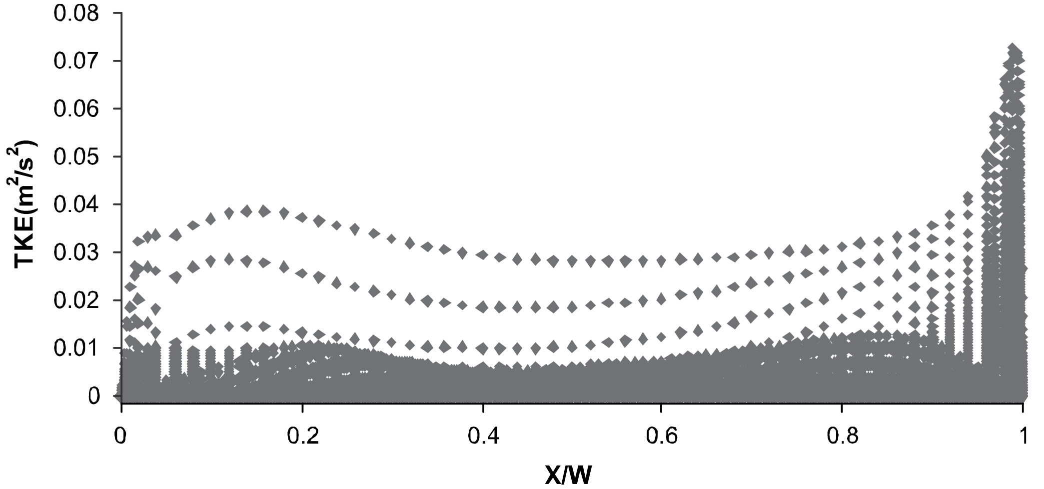
speed and that ultimately reduces the temperatures. However, it is also noted that the trends of TKE changes significantly in the wider canyon. Seemingly the low variation in the TKE curves in narrow street canyon bars the removal of heat from AR0.5.

NOMENCLATURE

AR	Aspect Ratio
H	Street Canyon Height (m)
W	Street Canyon Width (m)
X/W	Spatial Coordinate in Horizontal Direction Divided with Street Canyon Width
u_a	Horizontal Inflow Wind Speed (ms^{-1})
θ_g	Ground Level Temperature (K)
υ	Kinematic Viscosity (m^2/s)
$\overline{u_i}$	Mean Stream-Wise (u) and Vertical (υ) Velocity Components (ms^{-1})
p	Fluid Pressure (Pascal)
u,v,w	Velocity Components in X,Y and Z Directions (m/s)
Z/H	Spatial Coordinate in Z Direction Non-Dimensionalized by Street Canyon Height



(A). TURBULENT KINETIC ENERGY CONTOURS FOR AR 1.0 AND WIND SPEED 1.0 M/S



(B). TURBULENT KINETIC ENERGY CONTOURS FOR AR1.0 AND WIND SPEED 1.5 M/S

FIG. 5. CONTOURS FOR TURBULENT KINETIC ENERGY IN WIDE STREET (AR1.0) WITH VARYING AMBIENT WIND SPEED

$\theta_a, \bar{\theta}$	Ambient and Mean Air-Temperature (K)
$\Delta\theta_{s-a}$	Difference between the Surface and Ambient Air-Temperature (K)
υ_θ	Kinematic Diffusivity (m^2/s)
Re_H	Reynolds Number (Based on Street Canyon height) = u_aH/υ
$\overline{u'_iu'_j}$	Reynolds Stresses (m^2s^{-2})

ACKNOWLEDGEMENTS

The authors are grateful to Mehran University of Engineering & Technology, Jamshoro, Pakistan, for providing necessary help and facility to conduct this work. Additionally, the first author is thankful to the University of Hong Kong, Hong Kong, for providing necessary funding and support to carry out part of the simulation works.

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