USE AND EVALUATION OF THE ENVI-MET MODEL FOR TWO DIFFERENT URBAN FORMS IN CAIRO, EGYPT: MEASUREMENTS AND MODEL SIMULATIONS

Mohamed H. Elnabawi, Dr Neveen Hamza, and Dr Steven Dudek
School of Architecture, Planning and Landscape
Newcastle University, UK

ABSTRACT

In order to achieve outdoor thermal comfort it is necessary to understand the interactions between the prevailing climate, the urban form and roughness which lead to a distinctive micro-scale climate. The paper presents a micro-scale numerical model for two different urban forms within the same alley for a hot summer’s day in Cairo. In both cases, on-site measurements are used to validate the ENVI-met results which showed an overall agreement with the measurements, representing adequate Tmrt and PMV climatic map as an initial step in addressing the urgent need for a modelling platform accessible to urban designers, architects, and decision makers towards sustainable urban forms.

INTRODUCTION

The 4th IPCC Assessment Report indicated that Africa is warming faster than the global average, and this is likely to continue. This warming is greatest over the interior of semi-arid margins of the Sahara and central southern Africa. (IPCC, 2007). Warmer summer temperatures are expected to have a large impact on the quality of human life in urban quarters; these urban quarters differ from rural ones as they produce a pattern of distinct microclimatic systems, which results in hotter urban phenomena known as urban heat islands. A number of researchers focus on the environmental quality of urban open spaces and the description of microclimate processes (Hwang RL, Lin TP 2007, Lin TP. 2009, Huang L, Li J, Zhao D, Zhu J. 2008). Other studies focus on microclimate research and possible urban interventions to ameliorate thermal uncomfortable conditions such as Oke (1987), Bosselmann et al. (1995), Katzschner (2004), Matzarakis (2001), Moriwaki and Kanda (2004) and Stathopoulos (2006). Givoni et al. (2003) highlighted the designers' need for urban climatic predicting tools to evaluate the effect of urban microclimatic changes on outdoor human thermal comfort these tools need to provide the ability to process detailed environmental information according to time and location variations and to generate analytical results to reveal the relationship among the microclimatic environment, outdoor urban design and thermal comfort. In this study the microclimatic effects of two urban sites in the Islamic Quarter of Cairo is numerically assessed and compared to the numerical model ENVI-met 3.1.

THE CASE STUDY CONTEXT

Cairo lies between latitude 26° 50'N to 30° 45'N. In the centre of this area lies Al-Muizz Alley (Figure 1, 2), which is the urban site examined in this paper. It is one of the oldest streets in Medieval Cairo, approximately one mile long. In the late 90’s the UNESCO recognizing that Al-Muizz and its surroundings hold great historical and cultural value declared Islamic Cairo a protected world heritage site. The restoration project was commissioned by the Egyptian government, transforming the street into an open-air museum. The first part of the street was fully restored and was opened to the public in early 2010. The second part of the Alley has yet to undergo restoration. The present study contrasts the microclimate for each part of the same alley using ENVI-met numerical simulation, where each part has its own urban distinctive features, regulation, materials, shadings, vegetation, and surfaces etc. The case study is in a hot arid climate which is characterized by large diurnal temperature variations and sparse rain fall (group B according to Koppen classification) and in almost lies entirely in the sub group: BWh - arid or desert with hot climate (Peel MC, Finlayson BL, McMahon TA, 2007).

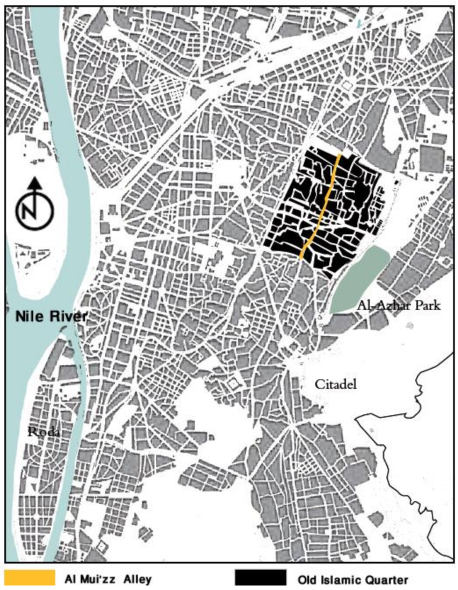

Figure 1 Al Muizz Alley location

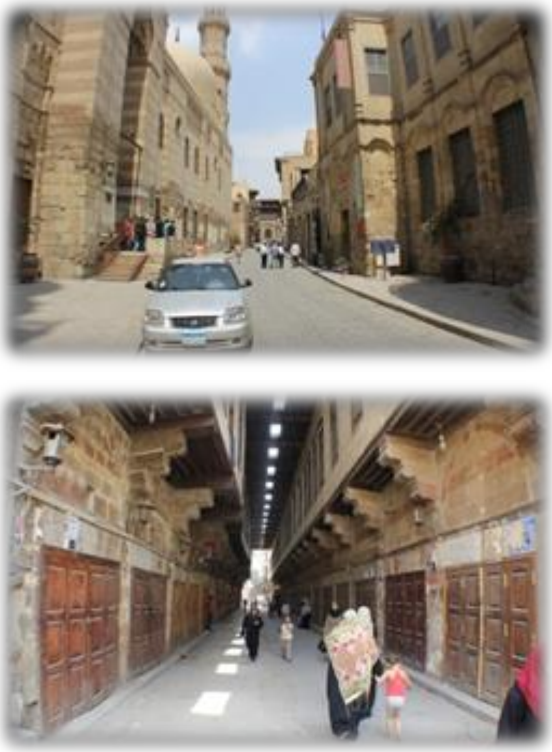

Figure 2 The renovated part on the top and the non renovated on the bottom

Based on 30 years of data from the metrological Station no.623660 records at Cairo international airport June and July are considered the hottest months. Small scale micrometeorology measurements were taken between 26th June and 2nd July 2012 representing the summer extreme. The physical parameters studied as stated in ASHRAE handbook (2009) are the air temperature, relative humidity, solar radiation and wind speed, in addition to globe temperature using the kestrel 4400 heat stress tracker. Figure 3 shows the instrument setup for measuring the five mentioned parameters. The measurement height was 1.1 m above the ground (a.g.l), corresponding to the average height of the centre of gravity for adults (Mayer and Hoppe, 1987). Figure 4, shows the two model domains as well as measurement points which were chosen to be representative of their respective neighbourhoods, to validate the modelling output.

NUMERICAL SIMULATION

The model simulations have been carried out with the three-dimensional non-hydrostatic climate model ENVI-met Version 3.1 (Bruse and Fleer 1998). ENVI-met can simulate the surface-plant-air interactions within urban environments with a typical resolution of 0.5 to 10 m in space and 10 sec in time. It calculates the dynamics of microclimate during a diurnal cycle (24 to 48 hours) using the fundamental laws of fluid dynamics and thermodynamics. The model includes the simulation of flow around and between buildings, exchanges processes of heat and vapour at the ground and vertical surfaces, turbulence, exchange at vegetation and vegetation parameters, bioclimatology, particle dispersion." (www.envi-met.com). According to Lenzholer, S. (2010), it is the only software where all the factors influencing thermal comfort like wind speed and direction, and mean radiant temperature (Tmrt) are simulated integrally to derive thermal comfort indices.

Figure 3 The mobile weather station setup

For the model simulations, the area around Al Muizz alley has been transformed into two model grids with the dimension 30 x 140 x 30 with a resolution of 1 m x 1 m x 3 m for the renovated part and the dimension 30 x 88 x 30 grids with a resolution of 1 m x 1 m x 3 m for the non renovated. Note that the model area is rotated 15° out of grid north. Table 1 shows the simulation input data for the 26th of June 2012 which is the extreme summer day for Cairo. Two snapshot measurments were located at the same spots of the measurement campaign to record Ta, RH, V, solar radiation and Globe temperature at 1.2 m above ground level (a.g.l). Outputs were then compared with the local climate scale averaged records for the same parameters observed from the site measurement.

Table 1.
Main input data used for ENVI-met

PARAMETER	***VALUE***
Ta, air dry bulb temperature	*301.95 ^{o}K*
RH, relative humidity	*59%*
V, wind speed	*3.5 m/s at 10m height*
soil temperature	*302 at (0-0.5m) and 299 at (0,5-2m)*
U value walls	*1.7*
U value roofs	*2.2*
Albedo walls	*0.4*
Albedo roofs	*0.15*

Figure 4 The 2 Modelling domains and the 2 measurement points

RESULTS AND DISCUSSION

Figure 5 shows the comparison between the measured air temperature at the two measurement points in 1.1 m a.g.l and the corresponding model results at 1.2 m a.g.l (due to the vertical model resolution..Two model simulation outputs are plotted against the data observed for the two parts of Al Muizz alley. ENVI-met estimation for the dry air temperature (Ta) were in a good approximation with the observed one in both parts as shown in figure 5 The air temperature (Ta) for the observed and Modelled reached their peak in the afternoon, between 11:00 and 13:00 in the renovated part, the observed air temperatures were between 33 °C and 33.69 °C comparing to ENVI-met air temperature of 31.27 °C and 30.95 °C respectively. In the non-renovated part, measured air temperatures were between 31.68 °C and 35.65 °C and the ENVI-met air temperature 30.12 °C and 30.03 °C respectively.

Relative humidity in figure 6 also showed a good agreement between the RH observed from the site measurement campaign and the RH generated by the ENVI-met, as they reached their maximum in the late morning between 6:00 till 10:00 for the renovated part where the observed RH was 72% and 50% corresponding to ENVI-met estimation which was 66% and 58% while for the non renovated was 78% and 56% against 64% and 64% as ENVI-met values

Figure 7 shows the Tmrt calculated using the 152 mm flat black globe thermometer compared to the Tmrt estimated by ENVI-met. The mean radiant temperatures calculated from the globe thermometers had to be recalculated using the observed in situ values to diminish the wind factor and the diameter of the globe according to equation (1) given by ASHRAE (2009) with empirical coefficient recently refined by Thorsson et al (2007) is:

$$T_{mrt} = \left[\left(T_g + 273.15\right)^4 + \frac{1.1 \times 10^8 V_a^{0.6}}{\varepsilon_g D^{0.4}} \times \left(T_g - T_a\right) \right]^{\frac{1}{4}} - 273.15 \qquad (1)$$

Where (T_g) is the globe temperature (°C),(V_a) is air velocity (ms^{-1}), (T_a) is the air temperature (°C), D [mm] is the globe diameter (= 152 mm), and ($\varepsilon_{\varepsilon g}$) is the emissivity of the sphere (=0.95 for a black globe).

The empirical derived parameter 1.1×10^8 and the wind exponent ($V_a^{0.6}$) together represent the globe's mean convection coefficient ($1.1 \times 10^8 V_a^{0.6}$).

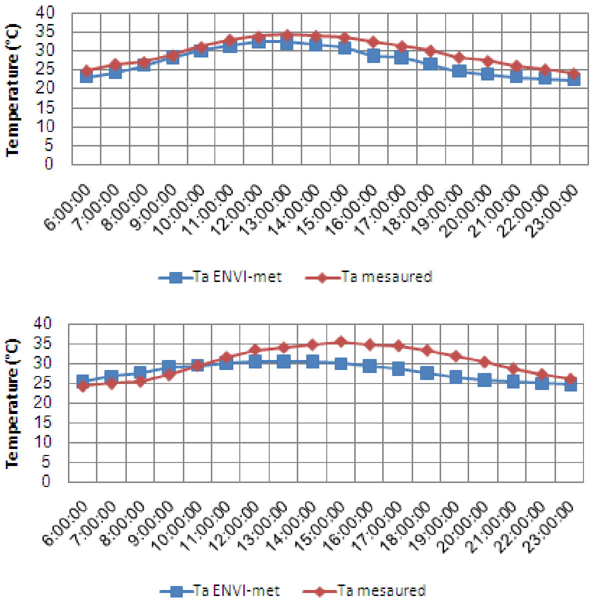

Figure 5 comparison between the dry air temperature measured and the ENVI-met output for the renovated (top) and non-renovated (bottom)

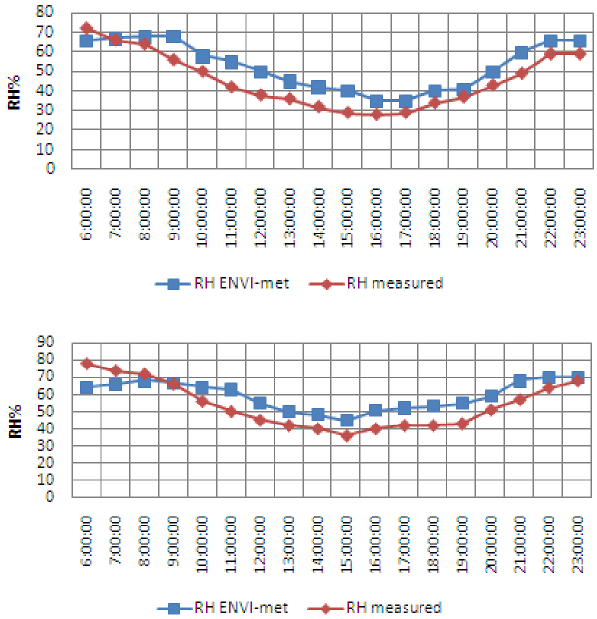

Figure 6 comparison between the Relative Humidity measured and the ENVI-met output for the renovated (top) and non-renovated (bottom)

The Tmrt (globe) at 13: was 43°C and at 16:00, 47.2°C at these times the Tmrt (ENVI-met) was calculated at 47 °C and 48.5 °C respectively, both reaching their peak at 15:00 with 53.1 °C Tmrt (globe) against 56 °C Tmrt (ENVI-met). Tmrt (globe) and Tmrt (ENVI-met) are about 19.5 and 13.5 °C respectively higher than Ta at the time of their maximum, till the sunset, when both Tmrt (globe) and Tmrt (ENVI-met) were dramatically fall down to almost reach the Ta and Tg values as the difference varies between 1 °C to 8 °C. ENVI-met predicted Tmrt showed good qualitative agreement with the measured Tmrt until sunset (18:00). Numerically it predicted value is higher than the measured, but does fall within the error band of measured Tmrt. After sunset the predicted value does not follow the measured value, suggesting the solar energy is not well accounted for the ENVI-met method. The same result was reported by Toudert, F., and Mayer, H. (2006), who found a good approximation between simulated Tmrt and measured yet ENVI-met underestimated the Tmrt value in the night time.

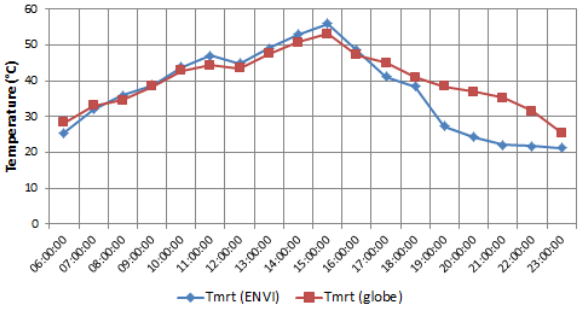

Figure 7 the mean radiant temperature Tmrt simulated by ENVI-met plotted against measured Tmrt

Once the Tmrt are known, the predicted mean vote (PMV) thermal index, as a single value that integrates the effects of the basic parameters in any human thermal environment, can be calculated by ENVI-met based on the heat balance equation (Fangers 1972) model (Bruse and Fleer 1998, Bruse 2008).

ENVI-met micro-scale climatic map

Figure 8, 9 shows the ENVI-met models for the spatial pattern of mean radiant temperature and predicted mean vote (PMV) (daily average measured at 1.2 m height).

The PMV is a thermal comfort index predicts the average thermal response, on a scale ranging from 1 (cold) to 7 (hot), of a group of people exposed to a set of environmental conditions. The Fanger's equation in its full form gives all human-related terms as a function of the internal heat production, together with Ta, Tmrt, VP (vapour pressure), v and the clothing insulation. PMV is calculated by ENVI-met based on the modified Fanger heat balance equation developed by Jendritzky and Nubler,, for outdoor conditions, shown in Equation 2

$$M + W + Q^* + QH + QL + QSW + QRe + S = 0 \qquad (2)$$

Where: (M) is metabolic rate (W) is mechanical power (Q*) is the radiation budget (a function of mean radiant temperature Tmrt and air velocity v), (QH) is turbulent flux of sensible heat (a function of air temperature Ta and v)., (QL) is turbulent flux of latent heat (diffused water vapour), (QSW) is turbulent flux of latent heat (sweat evaporation), (QRe) is respiratory heat flux (sensible and latent) and (S) is heat stored.

The mean radiant temperature (Tmrt) is one of the most important meteorological parameter governing human energy balance and It is the key variable in evaluating thermal sensation outdoors under sunny conditions regardless of the comfort index used (Mayer and Höppe 1987, Jendritzky et al. 1990, Mayer 1993, Spagnolo and De Dear 2003). Thus it has a strong influence on thermal sensation of the pedestrians using the open public spaces. In these view the models show specific areas with high PMV and Tmrt where action is needed. However, the non-renovated part of the alley revealed reductions in the whole neighbourhood pedestrian comfort records. This owed to several reasons, where the higher aspect ratio (height/width) and different street geometry causes less direct solar radiation to enter the alley and generally leads to lower Tmrt values throughout the most of the day which in turn affect the PMV (figure 10). In addition to increasing the albedo of the ground surface within the non-renovated part, as it is mix between the basalt and road bare ground against the basalt and granite of the renovated one with lower albedo value. This leads to strong solar irradiation in the renovated part compared to the non-renovated one that strongly influence the Tmrt where it reached its maximum to 56.1 °C against 53 °C in the non-renovated one (figure 9).

CONCLUSIONS

In this paper, the application of the ENVI-met averaging tool has been validated through comparing outputs of different parameters results to receptors output. All averages records occurred between the maxima and minima of receptors outputs of each case. Methodology composed of three steps; first, in situ measurements for each part of the alley including the main meteorological parameters and the globe temperature. Second, urban climate conditions of each case is simulated to have meteorological plots at the same certain points of the site measurements.

Finally, average outdoor meteorology for each case were observed and compared with the modelling output. ENVI-met reproduces the observed data with a sufficient accuracy. The conclusions of the analysis presented herein are summarized as follows:

1. Measurements and modelling of the outdoor thermal conditions has to be seen as a tool for urban planning and mitigation of a global climate change

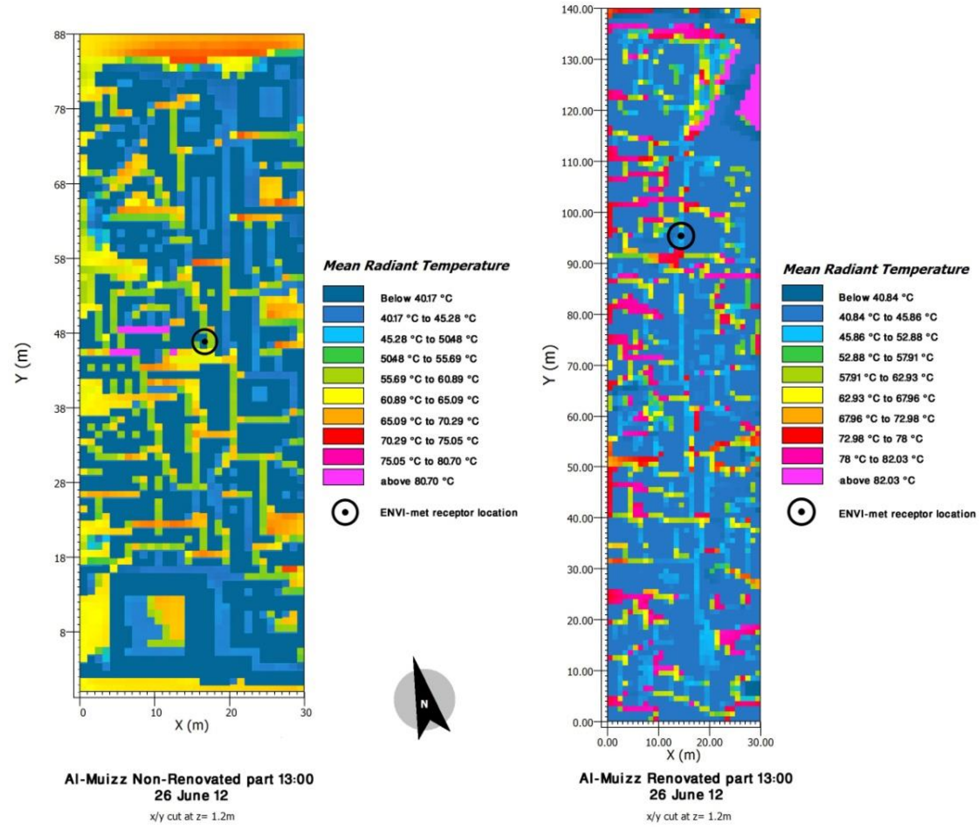

Figure 8 the spatial pattern of the Mean Radiant Temperature (Tmrt) for 26th of June 2012 by ENVI-met

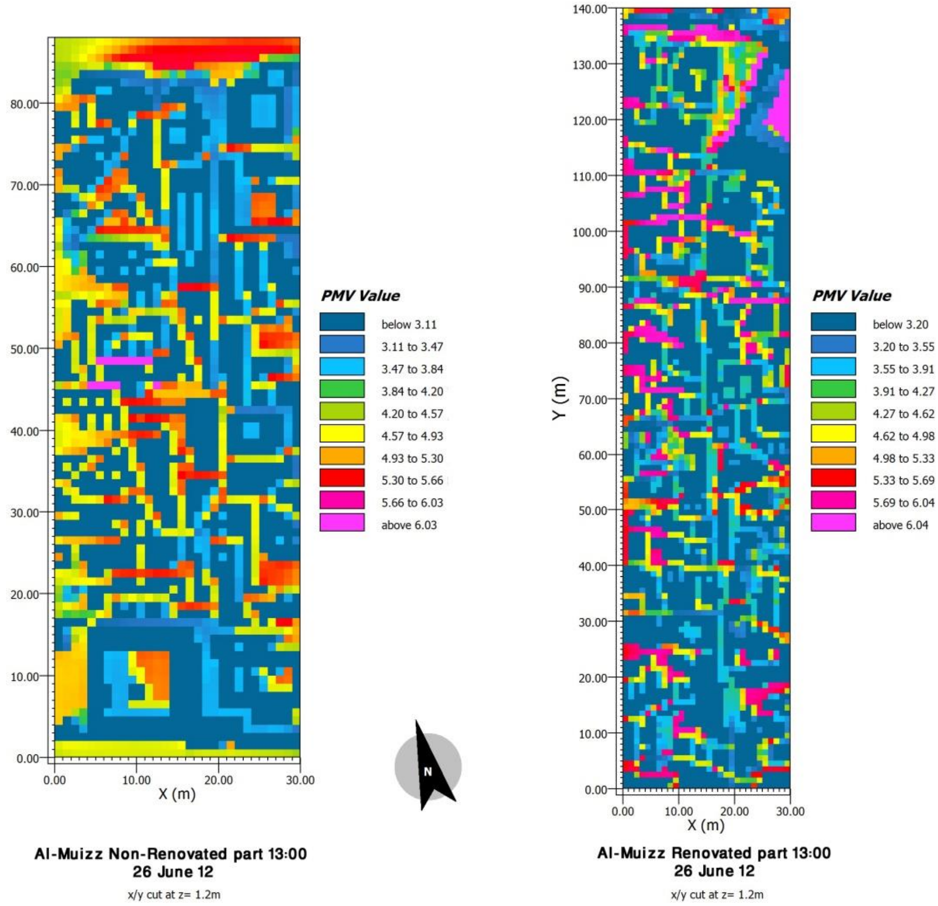

Figure 9 the spatial pattern of the Predicted Mean Vote (PMV) for 26th of June 2012 by ENVI-met

2. ENVI-met proved to be a reliable tool to simulate the different urban scenarios, thus, it is advisable for any planning process, or architectural intervention spatial distribution maps for the microclimate conditions similar to the one presented in this paper should be provided before construction.
3. The methodology described may contribute in developing guide-lines and standards for retrofitting open public spaces.
4. ENVI-met estimation for the Tmrt is in a good approximation as mentioned by Toudert, F., and Mayer, H. (2006), and that cope with the work of Thorsson et al (2007) and the heat balance equation for a surface in an urban canyon which is solved using the work of Kurn et al (1994).

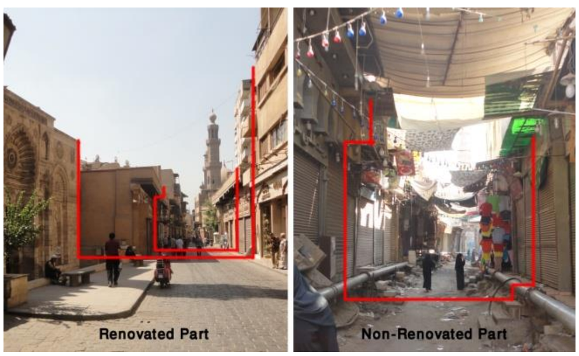

Figure 10 the H/Wand different urban geometry between the two parts

NOMENCLATUR

D = is the globe diameter [mm]
M = metabolic rate.
Q^* = radiation budget
QH = turbulent flux of sensible heat QL is turbulent flux of latent heat (diffused water vapour)
QSW = turbulent flux of latent heat (sweat evaporation).
QRe = respiratory heat flux (sensible and latent).
S = heat stored.
Ta = the air temperature
T_g = the globe temperature
T_{mrt} = the mean radiant temperature
T_{ground} = ground temperature
W = watt power
Va = air velocity
$\varepsilon_{\varepsilon g}$ = emissivity of the sphere

REFERENCES

Ali-Toudert F (2005) Dependence of outdoor thermal comfort on street design. PhD Thesis, University of Freiburg, Freiburg

Ali-Toudert F, Mayer H. 2005. Outdoor thermal comfort in the old desert city of Beni-Isquen, Algeria. Climate Research 28: 243–256.

ASHRAE. 2009 ASHRAE Handbook Fundamentals (Inch-pound Edition) American Society of Heating, Refrigerating, and Air-Conditioning Engineers, ISBN: 978-1-933742-54-0.

Bruse, M.2007. Simulating human thermal comfort and resulting usage patterns of urban open spaces with a multi-agent system. 24th Conference on Passive and Low Energy Architecture PLEA2007, Singapore, 24.

Bruse, M. 2006. ENVI-met 3 – a three dimensional microclimate model. Ruhr University at Bochum, Geographischer Institut, Geomatik. http://www.envi-met.com.

Bruse, M. 1999. The influences of local environmental design on microclimate, Ph.D Thesis University of Bochum, Bochum(in German)

Carfan, A., Galvani, E., Nery, J., 2012 Study of thermal comfort in the City of São Paulo using ENVI-met-model, Invest. Geog no.78 México ago.

Fahmy, M., Interactive urban form design of local climate scale in hot semi-arid zone, in School of Architecture. 2010, University of Sheffield: Sheffield.

Fahmy, M. and S. Sharples, Extensive review for urban climatology: Definitions, aspects and scales, in 7th International Conference on Civil and Architecture Engineering, ICCAE-7. 2008a: Military Technical Collage, Cairo May 27-29.

Givoni, B., Noguchi, M., Saaroni, H., Pochter, O., Yaacov, Y., Feller, N., et al. (2003). Outdoor comfort research issues. Energy and Buildings, 35(1), 77–86.

Jeannet M., Schuemperlin N., 2010, The Core of Cairo "Resistance to Comprehensive Gentrification" ETH Studio Basel Contemporary City Institute.

Heldens, W., 2010. Use of airborne hyperspectral data and height information to support urban micro climate characterisation The University of Würzburg

Huttner, S. 2012, Further development and application of the 3D microclimate simulation ENVI-met, Mainz University, Germany.

Kántor, N., Unger, J., 2011. The most problematic variable in the course of human-biometeorological comfort assessment – the mean radiant temperature Department of Climatology and Landscape Ecology, University of Szeged, Hungary

Karim, R., 2010. The Revival of Al-Muizz The Impact of Restoration on Islamic Cairo's Al-Muizzstree, Cambridge university.

Katzschner, L., Thorsson, S. 2009 Microclimatic Investigations as Tool for Urban Design, The seventh International Conference on Urban Climate,Yokohama, Japan.

Knez, I., Thorsson, S., Eliasson, I., Westerberg, U., Lindberg, F., 2008. Outdoor Place-Related Assessment: Towards a Conceptual Model, International Journal of Biometeorology, 53, 101–111.

Lahme, E.; Bruse, M. (2003): Microclimatic effects of a small urban park in densely built-up areas: Measurements and model simulations;ICUC5, Lodz

Lee, S.E. and S. Sharples. Analysis of the Urban Heat Island of Sheffield - the Impact of a Changing Climate. in Proceedings of PLEA2008 - 25th Conference on Passive and Low Energy Architecture. 2008. Dublin: PLEA.

Lenzholzer, S., and Koh, J. (2010). "Immersed in microclimatic space: Microclimate experience and perception of spatial configurations in Dutch squares." Landscape and Urban Planning, 95, 1-15.

Liang C, Edward Ng, (2012) outdoor thermal comfort and outdoor activities: a review of research in the past decade. Cities, 29, 118-125.

Lin, T.-P. (2009). Thermal perception, adaptation and attendance in a public square in hot and humid regions. Building and Environment, 44, 2017–2026.

Matzarakis A., Rutz F., Mayer H., Modelling radiation fluxes in simple and complex environments: basics of the RayMan model. Int. J. Biometeorol., 2010, 54, 131-139

Matzarakis A, Rutz F, Mayer H. 2000. Estimation and Calculation of the mean radiant temperature within urban structures. In Biometeorology and Urban Climatology at the Turn of the Millennium, Macquarie University, de Dear RJ, Kalma JD, Oke TR, Auliciems A (eds).: Sydney; 273–278, ICB-ICUC'99, WCASP-50, WMO/TD No 1026.

Nikolopoulou N, Baker N, Steemers K. 1999. Improvements to the globe thermometer for outdoor use. Architectural Science Review 42: 27–34.

Nikolopoulou M., Baker N., Steemers K., Thermal comfort in outdoor urban spaces: Understanding the human parameter. Sol. Energy 2001,70,277

Sutton, K., and Fahmi, W. (2002). The Rehabilitation of Old Cairo. Habitat International. 26, 73-93.

Thorsson, S., Lindqvist, M., Lindqvist, S., 2004. Thermal bioclimatic conditions and patterns of behaviour in an urban park in Göteborg,

Thorsson S., Lindberg F., Eliasson I., Holmer B. 2006. Measurements of mean radiant temperature in different urban structures. In 6th International Journal of Biometeorology,48,149-156.

Thorsson S., Lindberg F., Eliasson I., Holmer B. 2007. Different methods for estimating the mean radiant temperature in an outdoor urban setting. International journal of climatology. 27: DOI: 10.1002/joc