Pedestrians' Comfort Index in Urban Settlements Using CFD Analysis

M. Navvab[1] and J. Varodompun[2]

[1 2] TCAUP College of Architecture, the University of Michigan,
2000 Bonisteel Boulevard, Ann Arbor, MI. Phone 734-763-2159

ABSTRACT

Application of scale models along with the use of wind tunnel testing facility have been the primary tool used in building aerodynamic studies by architects and planners. Problem areas in a given airflow study could be identified by an experience wind engineer; however, the timely sharing the results with the design team becomes essential for a successful project. This paper a describes new approach using Computational Fluid Dynamics (CFD) modeling that includes the effects of wind speed, temperature, relative humidity, clothing, activity, solar radiation as an index for pedestrians' comfort in urban settlements. The study shows the CFD is a reliable alternative design tool given ease of access, use and rapid feedback through various post processing of the results in simulation and contributes to the accelerated design decision making process at all stages of the project

KEYWORDS
Pedestrian Comfort, CFD, Solar Radiation, Wind Velocity, Urban Settlements

INTRODUCTION

Major urban areas with tourist attractions require walkways for pedestrians. A windy or uncomfortable exterior environment will detract from the entry to the site or perhaps from visiting the building given the seasonal conditions. Studies have shown many factors such as local climatic conditions, building massing, its' surface reflectance, and the landscape of the terrain within a given site influence the wind conditions at the pedestrian level. Horizontal wind flows with high velocities are reduced by planting. Podiums and canopies mitigate high energy winds, brought by downward flows.

Understanding comfort criteria for pedestrian level wind environment has been a contributor to safety and commercial success of major developments in cities and or urban areas with high concentrations of the buildings occupied by the entertainment industry. The comfort criteria for pedestrians should not only include the wind speed and direction, but also its' frequency and persistence over a range of activities by vulnerable pedestrians in a given window of time. Researchers have also added other variables such as solar radiation and humidity (Soligo, et aL.1998).

Airflow studies can have a significant influence on the results of building aerodynamic studies that are conducted in wind tunnels. Investigating these effects by means of wind-tunnel would require considerable parametric tests and needed geometrical changes by the design team while away from the testing facility which is time-consuming and expensive. Although the accuracy of this method is well defined, the availability and the limitation of the discrete number of measurement points given the size of the models used in these testing facilities, require time and funding. The availability and the timely sharing of the results with the design team at various stages of the design become essential for a successful project (Durgin, 1997).

The current advancements in CFD complex flow modeling (even for steady state solutions) through more detailed 3-D architectural models as compared to physical mass models used in wind tunnels make the CFD, one of the most reliable alternative design tool. CFD ease of access, use and rapid feedback through various available post processing options represents a new approach in simulation and contributes to the design decision making process at all stages of the design. There has been and will be more discussions on the advantages of the CFD over wind tunnel testing (Wright, 2004), however, this study will focus on implementation of the human comfort model in CFD simulation, and its application for urban settings.

METHOD AND APPROACH

In this paper, a CFD study of the influence of various building geometry is preformed. Large-scale buildings change the wind velocity at the grade level, hence the comfort of the users and or the pedestrians. The use of CFD modeling to estimate the wind force at the ground level has provided opportunities to examine the environmental boundaries in order to develop more comprehensive criteria that include human comfort more accurately for urban areas. Currently, CFD is increasingly used in many wind force or ventilation studies. The CFD method is sensitive to setup parameters (Zhang, 2005). As part of the protocol for CFD modeling the systematic recording of the parameters is recommended. The standard calculation conditions are stated for any future validation or comparative study based on the proposed standards (Yoshie et al., 2005, Moonen, 2005).See **Table 1**.

Table 1: Standard Calculation Conditions

Computational Domain (C.D.)	The size of the test section of the wind tunnel
Grid Resolution	No. nodes=270084, No.elements=1156341, edge/length ratio=461
Scheme for advection term	2^{nd} order upwind for U,V,W,k,ε, with Physical Time scale
Building and ground surface	Logarithmic for smooth surface wall
Upper and side surface of the (C.D)	Free Slip wall condition
Turbulence Model	Standard k-ε Model
Inflow Boundary Condition (Power Law)	Velocity profile = Vref*(z/Zref)^a, a=.14 for urban settings
Outflow Boundary Condition	Zero gradient condition

The heat balance of a human body under a given time of exposure and a climatic condition is affected by temperature, humidity solar radiation, wind speed, frequency of it persistence, clothing, activity and body position (ISO 7726, 1984). Predicted Mean Vote (PMV) can be used to describe comfort range statistically. The calculation is based on heat energy balance between human body and environment (ASHRAE, 81, 89, 99, 2001 and 2005). Thus, PMV relies on personal and environmental factors. The former includes metabolism (M), work (W), and clothing (f_{cl}). The latter consists with room temperature (t_a), radiation (t_r), humidity (P_a), and wind velocity (h_c). PMV calculation relies on SI system. Metabolism (M) depends on foods and breathing rates. The typical occupants' metabolic rate per skin surface area can be found in **Table 2**. Due to inefficiency of the human body, work (W) can only be generated at 20% of a given metabolic rate. Clothing area factor (f_{cl}) is calculated from Clo-value (I_{cl}) shown in **Table 3**. If Clo-value is more than 0.5, **Equation 1a** and for others **Equation 1b** are used. Besides the air temperature, mean radiation temperature (tr) can be obtained by globe thermometer in full scale measurement or calculated by **Equation 2** within CFD simulation. Vapor pressure can be obtained from psychometric chart or using **Equation 3,** if humidity level (w_p) is given. Air velocity reduces air film resistance and increase evaporation rate. As a result, heat is removed from the body faster. Convective heat transfer coefficient (h_c) is reflected in PMV calculation. Highest hc is picked by either **Equation 4a or 4b**. PMV calculation is presented in **Equation 5**. The effect of clothing (t_{cl}) is presented in **Equation 6** (Awbi, 2003).

Table 2: Metabolic rate of typical activities

Activities	Metabolic rate (W/ m^2)
Reclining	46
Seated, relaxed	58
Standing activity (shopping)	93
Medium activities (garage work)	165

Table 3: Clo-value of typical clothing

Clothing ensemble	I_{cl} (clo)
Node	0
Short	0.1
Light work ensemble	0.7
Typical Indoor winter cloth	1
Heavy Business suit	1.5

Table 4: Equations for PMV parameters:

Equation 1a (top) Equation 1b (bottom)	Equation 2	Equation 3	Equation 4a (top) Equation 4b (bottom)
$fc = 1.05 + 0.1 I_{cl}$ $fc = 1.00 + 0.1 I_{cl}$	$Q_{rad} = 5.6705 \times 10^{-8} t_r^4$	$w_p = 0.62 \times 10^{-5} P_a$	$h_c = 2.38 (t_{cl} - t_a)^{0.25}$ $h_c = 12.1 \sqrt{v}$
I_{cl}= Clo-value (Clo) f_{cl}= clothing area factor	Q_{rad}= radiation energy (W/m^2) t_r = mean radiation temperature (K)	w_p=humidity level (kg/kg) P_a=water vapor pressure (Pascal)	h_c=heattransfer coefficient (W/m^{2}K) t_{cl}=clothing temperature (C) t_a=air temperature (C) v=air velocity (m/s)

$$\boldsymbol{PMV} = (0.303 e^{-0.036M} + 0.028)\{(M - W) - 3.05 \times 10^{-3}[5733 - 6.99(M - W) - P_a] - 0.42[(M - W) - 58.15] - 1.7 \times 10^{-5} M (5867 - P_a) - 0.0014 M (34 - T_a) - 3.96 \times 10^{-8} f_{cl}[(t_{cl} + 273)^4 - t_r^4] - f_{cl} h_c (t_{cl} - t_a)$$

Equation 5

$$\boldsymbol{t_{cl}} = 35.7 - 0.028(M - W) - 0.155 I_{cl}\{(M - W) - 3.05 \times 10^{-3} \times [5733 - 6.99(M - W) - P_a] - 0.42[(M - W) - 58.15] - 1.7 \times 10^{-5} M (5867 - P_a) - 0.0014 M (34 - t_a)$$

Equation 6

The mathematical relationship used in PMV calculation incorporates all thermal parameters. This function represents a steady state energy balance which assumes a state of equilibrium. Since 1967 various indices have been introduced to show the state of human comfort for indoor environments (Stenberg, 2004, Doherly,1988) such as Predicted Mean Value (PMV), Thermal Discomfort (TDIS) and the thermal sensation index using by Fanger ranges from -3(cold), -2(cool),-1(slightly cool), 0 (neutral), +1(slightly warm), +2(warm), and +3(hot) (Fanger, 1973). These models are flexible and it is possible to reflect the regional variations and their climate changes. The advancement in CFD modeling and availability of interface with their predefined macros (mean radiant or resultant temperature) in this case used in ANSYS-CFX10 and other software such as psychometric chart used in SQUAREONE, 2000 present opportunities to examine the assessment of the thermal comfort criteria offered by many researchers (Emmerich, NIST 2001). The PMV-PPD index is an appropriate and easily understood expression for the quality of a given thermal environment. These indices have been adopted by ISO/DP 7730 and recommended as the thermal indices for moderate thermal environments. The pedestrians comfort was calculated by using the above equations along with the weather data processing utility programs utilized by the energy software, eQUEST (eQuest DOE, 2004). Simulation can be setup with local temperature, wind force velocity, dominant wind direction and solar and humidity levels based on the hourly weather file statistics for the particular location. The velocity ratios obtained from CFD models are used as inputs in a separate macro utilizing the latest wind chill functions.

The statistical processing of the final results are based on the data points generated by the CFD post processing model for their evaluation against the comfort criteria for tolerable conditions offered by different organizations. **Tables 5, 6** and **7** show such examples based on the comfort criteria threshold for tolerable conditions using wind speed in Beaufort force scale as converted to km/h (Lawson, 1978).

Table 5: Lawson comfort criteria thresholds

Prescribed Usage	Unacceptable	Tolerable
Road and car parks	6%>39 km/h	2%>39 km/h
Business walking	2%>39 km/h	2%>31 km/h
Pedestrian walk through	4%>31 km/h	6%>23 km/h
Pedestrian standing	6%>23 km/h	6%>23 km/h
Entry doors	6%>23 km/h	4%>23 km/h
Sitting	1%>23 km/h	4%>23 km/h

Table 6: Wind force criteria

Category	Wind Velocity	Frequency
Sitting	0-9 km/h	>=80%
Standing	0-14 km/h	>=80%
Walking	0-18 km/h	>=80%
Uncomfortable	>18 km/h	>=20%
Severe	>=52 km/h	>=0.10%
Danger	>55 km/h	N.A

Table 7: Thermal sensation scale used as comfort criteria

Description	Intolerably Hot	Very Hot	Hot	Warm	Slightly Warm	Neutral	Slightly Cool	Cool	Cold	Very Cold	Intol. Cold
Number	+5	+4	+3	+2	+1	0	-1	-2	-3	-4	-5

RESULTS AND ASSESSMENT OF THEIR SIGNIFICANCE

Given the standard calculation stated in **Table 1** for modeling, the existing and the proposed (new) buildings in an urban setting were evaluated for their influence on the pedestrians comfort. The meshing of these large scale urban development projects comprises both unstructured tetra and prism layer (1.15 million elements). See **Figure 1**. The prism layer allows the results near boundary layers to be more accurate (ANSYS, 2005). To optimize the simulation time, steady state with 40 iterations with second order upwind are used. The Fanger's function is incorporated as a CFX Command Language (CCL) as predefined macros within its modeling capability. Simulation scenarios are setup for hot/dry and or hot/humid climatic conditions. These scenarios are based on wind load variations for high, medium, and low wind velocities (144, 65, 32 Km/h), while the solar radiation loads (300, 600, 900 W/m^2) are added as additional inputs. Overall strategies to mitigate the discomfort were added by the design teams around the new or proposed buildings. The parametric runs were conducted for each design (before/existing and after/new) using the proposed index for pedestrian comfort. This approach allows for more specific studies such as the pedestrian activity given the wind force, human thermal comfort, and wind chill, solar glare and access, street-layouts, and noise and air quality (to be added in the future). The post data processing macro includes the first five variables. A criterion based on these five variables is one method of evaluation; however, integration of these factors shows a significant improvement over criteria based only the wind force. The results and the assessment of the findings are presented in Figs. 1 to 4. This approach is used as planning tool and the summery of the study is used as a decision making guide by developers, architects, engineers and the public or community planners. The wind velocities are adjusted for the urban cityscapes inlet velocity profile based on the power law (Simiu,1978) using the CCL predefined function within the CFD- CFX modeling capability given the local wind force time averaged peaks (Durgin, 1997). The reduced wind velocities due to the addition of the new buildings improved the PMV in winter. The wind shaded areas in summer bring higher comfort level given this hot/dry climatic condition. The added new buildings provide shade during the summer at the ground levels. Wind velocity exceeding the discomfort threshold levels are eliminated in areas close to the new buildings. See

Figure 2. **Figure 3** shows the wind pressure influence on the surfaces and walls with various glazing types. The new modified PMV index shows the pedestrian thermal comfort conditions due to the new added buildings as compared to the empty site. The top view of the entire site shows a snap shot of the overall pedestrians' comfort conditions given the cityscape and the selected climatic condition. This also provides fast feedback during the design process and used as a frame of reference for comparison of different design alternatives such as building heights, tilt of angels and distance to the adjacent buildings or properties. See **Figure. 4.**

Figure 1: Simulated results of the 3D-meshing using CFD modeling.

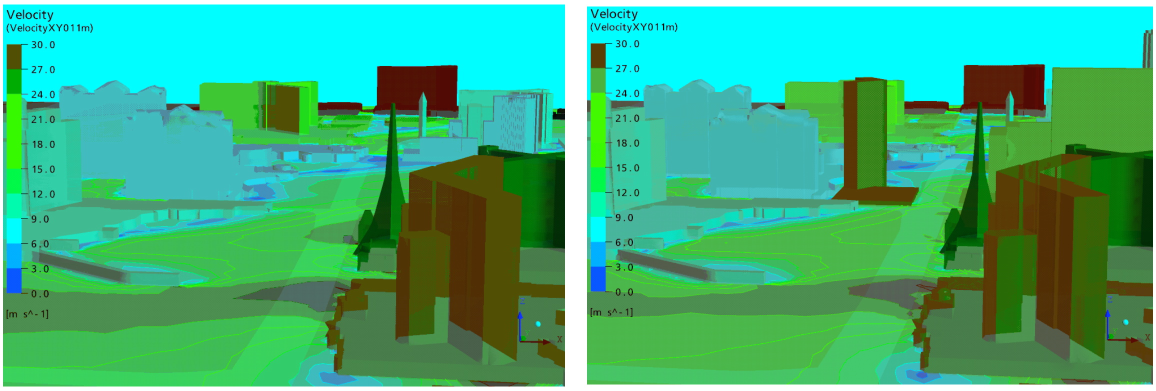

Figure 2: Simulated results at the pedestrian level from the144(km/h) wind velocity.

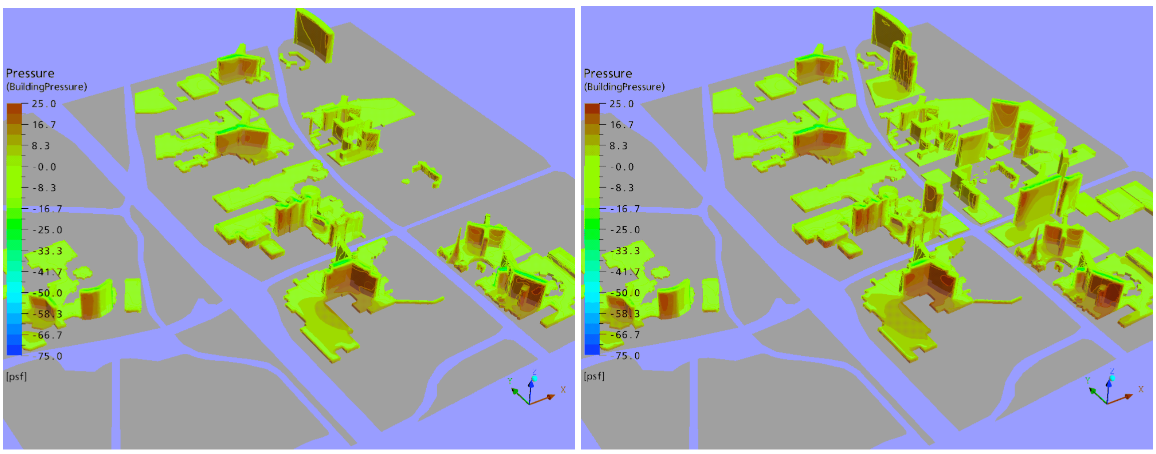

Figure 3: Simulated results at the pedestrian level from the 65 (km/h) wind velocity.

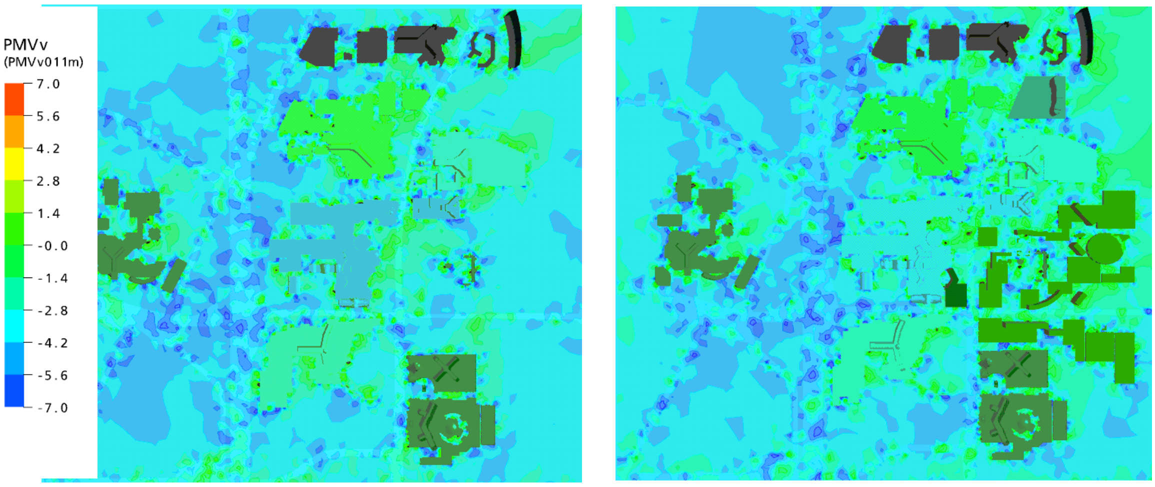

Figure 4: Simulated results at the pedestrian level from the 65 (km/h) wind velocity.

CONCLUSION

The comfort index presented in this paper integrates all factors affecting pedestrians, into a single predictive model for urban environments. These factors and their interaction within a given urban climatic condition are simulated using CFD modeling. This approach facilitates obtaining a single index representative of the human comfort conditions simultaneously. The results of this study will contribute to a set of guidelines for the use of CFD for prediction of human comfort at the grade level within the urban sites under various climatic conditions. Although the current index is comprehensive for its planning application, the CFD provides future opportunities to examine additional variables that could not be included in the comfort assessment.

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