Assessment of thermal and mechanical comfort of people based on wind tunnel experiments

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1. INTRODUCTION

Outdoor spaces in cities are used by the population to perform different activities. The conditions of the atmospheric environment and the meteorological variables, such as temperature, humidity, solar radiation and wind influence the usage of these spaces and never before microclimatic conditions had so much attention, because they contribute to the quality of life from an economical an social point of view (Stathopoulos, 2006). Wind can affect both thermal and mechanical comfort at the pedestrian level and strong winds can even become, in specific situations, a hazard to people (Lopes et al., 2007). Mechanical discomfort in pedestrian walkways and open spaces due to strong winds has worsen in recent years, due to urban growth and development, new types of buildings, namely high-rise, open space configurations and inappropriate urban design. Additionally, human perception of the atmospheric environment, which also affects the usage of these areas and the comfort of its users, is a complex issue, since it is influenced by numerous factors of diverse nature. Besides that, the definition of mechanical comfort thresholds is also a hard task, because the relation between pedestrian comfort and wind speed depends on clothing, gender, age, activity, among other factors and because the frequency of disturbing wind speeds and the average values and gusts in urban canyons aren't always known.

The first attempts to assess mechanical comfort thresholds date back from the 1970's (Penwarden, 1973) but these thresholds are not well adapted to the southern Europe population. This research, which is part of the UrbKlim project[1], aims to determine thresholds of mechanical and thermal comfort on human beings when wind conditions change, considering the specific characteristics of the Portuguese population and environment, through experiments in an aerodynamic wind tunnel. Saraiva et al. (1997) found that, with a wind-effective speed greater than 9 m/s, the performance of a pedestrian in a street is significantly affected, while an effective wind greater than 20 m/s is hazardous for weaker persons. Experiments conducted in a wind tunnel with a physical model of the eastern part of Lisbon showed many critical points in the streets, in a safety perspective, and that more than 43 hours per year could be critical, with effective wind velocities greater than 20 m/s. It is also important to consider that there have been many different results in relation to wind speed thresholds for the assessment of comfort, in addition to the large diversity of parameters used (Koss, 2006; Sanz-Andres and Cuerva, 2006;).

In this study, metabolic process, solar radiation and mean radiant temperature were not taken into account to assess thermal comfort because it is difficult to control these variables in a wind tunnel. However, a first attempt was made to include clo insulation and body surface area, besides the control made on the activity of the participants (they were all doing the same thing at the same time, either standing still or walking). In what concerns mechanical comfort, wind turbulence (gusts) have not yet been tested. In future experiments, a way of simulating the transition from calm to a strong turbulent environment will be tested.

2. METHODS

A set of experiments with 36 persons aged from 20 to 56, was carried out at the wind tunnel of the National Laboratory for Civil Engineering (LNEC), in Lisbon, in November 2006 and February 2008 (the temperatures varied between 16ºC and 18.3ºC, inside the tunnel, in both experiments). The wind

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[1] UrbKlim Project, POCI/GEO/61148/2004, financed by FCT (Portugal) and by the Operational Programme for Science and Innovation 2010.
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tunnel is a Boundary Layer Wind type with a test area 9 m long and a cross section of 2x3 m^2. The wind velocity can be continuously regulated up to 18 m/s.

Before entering the tunnel, the participants filled in a questionnaire with information about age, weight and height, health condition and clothing, in order to analyse the relation between these individual characteristics and the levels of comfort and mechanical response to wind. CLO values were also computed for each individual in order to assess clothing influence and thermal response of the participants. The participants were subjected to three different trial runs:

i) Degree of thermal, mechanical and general comfort. The participants, divided in groups of 5 people and dressed with 2 layers of clothing on their upper bodies and jeans, were standing still inside the tunnel, in such a way that minimizes flow disturbance and were subjected to 6 different levels of wind speed (from 1.6 to 9.1 m/s); in each level, there was an acclimatisation period of 5 minutes, after which the participants filled in a questionnaire concerning their degree of comfort (fig. 1).

ii) Level of thermal response. The participants, wearing only a layer of clothing and standing still inside the tunnel, were exposed to the same levels of wind speed as the previous trial but with acclimatisation periods of 3 minutes; they were asked to leave the tunnel when they felt the extreme need to put on more clothing in order to maintain thermal comfort. The level of wind speed that made each participant leave the tunnel was then recorded.

iii) Movement capability. The participants were divided in groups of 2 or 3 people and were constantly walking in a space of 6 metres inside the tunnel, with 6 different levels of moderate to strong wind speed (ranging from 7.5 to 18 m/s). The degree of difficulty to walk was registered for each wind velocity in the questionnaire provided (fig. 1).

3. RESULTS

The preliminary results are the following:

i) Considering the thermal effect, it was found that 50% of the people felt comfortable up to 2.5 m/s and 80% felt cold or very cold with 4.5 m/s (fig.2). For this wind speed only 20% of the participants stated that they were not cold. For wind speeds above 6.5 m/s, all participants declared being cold or very cold and at 7.5 m/s, 11% stated it was difficult to support, all of them were women. Above 9 m/s 20% felt it was very difficult to support (from these, almost 70% were women), while the other participants stated being cold and very cold. These thresholds were very similar to those found when people were asked about the wind speed perception (fig.3): everyone felt neutral or light wind until 2.5 m/s; 90% felt windy at 3.5 m/s and everyone felt windy and very windy at 6 m/s. At 9 m/s more than 30% declared to be difficult to support the wind. As for the general comfort levels, 50% of the participants declared to be comfortable at 3 m/s, at 4.5 m/s 20% declared being comfortable and 11% stated they were very uncomfortable, 75% of these were women. At wind speeds of 7 m/s 85% were uncomfortable or very uncomfortable (fig. 4) and with wind speeds of 9.1 m/s this percentage increased to 97%. In table 1 we summarize these results.

ii) The thermal resistance tests revealed that at 4.4 m/s, 50% of the participants had already left the tunnel and only 8% of the participants still remained inside the tunnel after 6 m/s (fig.5).

iii) For the difficulty felt in moving, which was tested for wind speeds between 7.5 and 18 m/s, the results showed that, with wind speeds of 7.5 m/s, all participants felt no difficulty in moving. 14 m/s seems to be the wind speed transition from moderate (some difficulty) to very difficult to walk (critical limit – fig. 5). At 18 m/s, the majority of the individuals (93%) found it difficult (23%) or very difficult (70%) to move, and 3% couldn't walk. At a wind speed of 13 m/s, 29% of the participating women found it difficult and very difficult to walk, against 25% of men; at a wind speed of 14.7 m/s, this percentage increased to 79% for women and 56% for men. On the contrary, at 17 m/s, a higher percentage of the participating men find it difficult or very difficult to walk (94% men and 86% women). It must be taken into consideration that data were analysed considering only two classes: the ease or difficulty to walk and not all the classes available, which will be analysed in future research.

An attempt to qualify the comfort and relate it with thermal resistance and difficulty of movement was made and is presented in table 2.

4. DISCUSSION

The experiments have shown that the increase in wind speed results in changes in the level of thermal and general comfort. Temperature and relative humidity were kept constant, thus they do not account for the changes in comfort level. Other factors must be considered, such as personal characteristics (age, gender, clothing) and preferences. In field surveys carried out in outdoor public spaces of Lisbon during 2006 and 2007, which consisted on interviews and simultaneous measurements of meteorological variables in every season, it was found that the thermal preferences are strongly associated with wind speed (Andrade et al., 2008). Furthermore, the authors also found that the acceptability of warmer conditions outdoors is higher than for cooler conditions and that the majority of the people interviewed (circa 1000) preferred to decrease wind speed in order to improve their comfort level, in all the seasons. These preferences can partly explain the changes in comfort level that resulted from the increase in wind speed inside the wind tunnel.
In the experiments, women showed a lower tolerance to cold conditions and to higher wind speeds than men, which is in accordance with previous studies which showed that gender can also influence the comfort level associated with wind speed (Makinen et al., 2006; Oliveira and Andrade, 2007).

The thresholds we found are similar to those found by Penwarden (1973); in our experiments, with a wind speed of 4.5 m/s more than 60% of the participants were uncomfortable or very uncomfortable. Penwarden (1973) stated that a mean speed of 5 m/s seemed to represent the onset of discomfort. This author also stated that wind speeds of 10 m/s could be classed as definitely unpleasant and in our experiments, at a wind speed of 9.1 m/s, the majority of people (83%) declared being very uncomfortable; this value increased to 97% when considering also the class of "uncomfortable".

There are differences between genders when considering the difficulty to move; women found it more difficult to walk than men at lower wind speeds. This may be due to physiological differences between genders; in further studies, Body Surface Area and other indices will be computed in order to assess the influence of the physiological characteristics in the movement capability. According to Jordan et al. (2008), a safe wind speed is the one that does not cause a person to loose the balance; for wind speeds up to 17 m/s, nobody said they couldn't walk, even though it could be very difficult, but at 18 m/s (the maximum speed tested) 3% said they couldn't walk. These results are in accordance with Penwarden (1973) and Saraiva et al. (1997), since they found that only a wind speed of at least 20 m/s is hazardous to people, particularly to old and infirm persons, which were not tested in our experiments.

5. CONCLUSION

Wind is one of the factors that can influence the level of comfort of pedestrians (Stathopoulos, 2006). The experiments in the wind tunnel have shown that an increase in wind speed to a higher level, after a short period of acclimatisation, and maintaining the other meteorological variables constant, results in changes on the level of thermal and general comfort felt by people. Furthermore, personal characteristics, such as gender and clothing, can also influence human comfort. These tests served as a starting point to the definition of thresholds of thermal and mechanical comfort applied to the Portuguese population.

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Table 1 – Summarized thresholds (m/s) for all experiences

	Comfortable	Cold and windy	Very uncomfortable and windy	Difficult to bear
Thermal	2.5	4.5	6.5	9.0
Wind	2.5	3.5	6.0	9.0
General	3.0	4.5	7.0	9.0

Table 2 – Thresholds of comfort

	(m/s)
Comfortable	< 3.0
Cold and windy	3.0 - 7.0
Very uncomfortable and windy	7.0 - 9.0
Difficult to bear	> 9.0

Nr.								
Temperature		**No wind**	**V1**	**V2**	**V3**	**V4**	**V5**	**V6**
Hot	1							
Neutral	0							
Cold	-1							
Very cold	-2							
Difficult to bear	-3							
Wind								
Airless	-1							
Neutral	0							
Windy	1							
Very windy	2							
Difficult to bear	3							
General comfort								
Very comfortable	1							
Comfortable	0							
Uncomfortable	-1							
Very uncomfortable	-2							
Movement			**V1**	**V2**	**V3**	**V4**	**V5**	**V6**
Easy to walk	0							
Some difficulty	1							
Difficult to walk	2							
Very difficult	3							
Can't walk	4							

Fig. 1. Questionnaire filled in by the participants

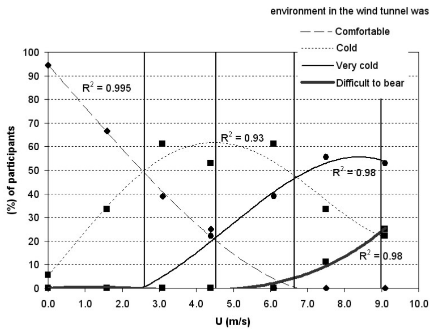

Fig. 2. Thermal effect

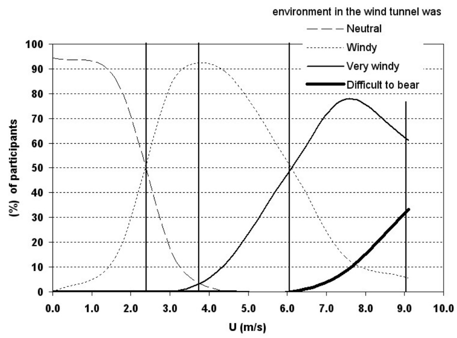

Fig. 3. Wind speed perception

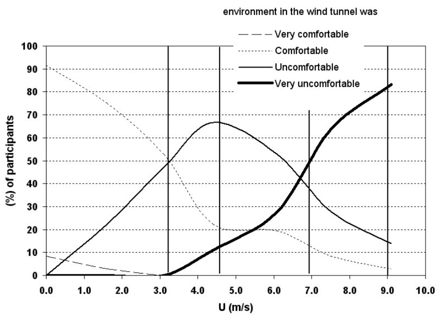

Fig. 4. General comfort

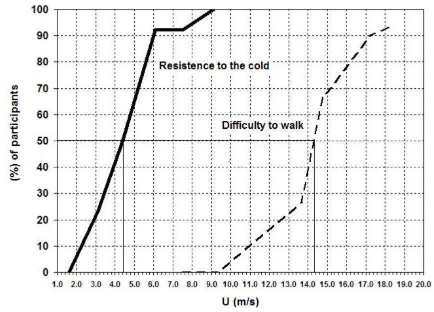

Fig. 5. Thermal resistance and difficulty felt in moving