REDUCED SCALE APPROACH OF TENT NATURAL BUOYANCY AND WIND-DRIVEN VENTILATION

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Sophie Herpin[1], Xavier Faure[2] and Hervé Brébion[2]
[1]Oxylane, Thermal Comfort Laboratory, Villeneuve d'Ascq, France.
[2]CSTB, CAPE department, Nantes, France.

Abstract
The present contribution consists in a reduced-scale approach of buoyancy and wind-driven ventilation inside a classical family tent of moderate dimensions (5.4m long, 1.85m high and 2.3m large). The similarity hypothesis chosen are based on the internal Archimedes number and volumetric flow rates through the tent openings. Both the full scale and a reduce-scale model (1/2) are investigated in a climatic wind-tunnel, and the similarity hypothesis can hence be assessed experimentally. The measurements performed inside the tents are focused on global quantities: air change rate obtained with the tracer gas technique, and mean thermal gradient in height. In order to maintain the same Archimedes number (and hence the global air column weight), the thermal gradient in the half-scale model needs to be twice bigger than for full scale. This is achieved by increasing the tunnel radiation intensity on the reduced-scale model. The similarity hypotheses are studied for different configurations, by varying the wind orientation and speed, and the surface area of the tent openings. The application of the reduce-scale methodology is finally identified as relevant, and some limitations are pointed out, mostly for forced convection regime.

Keywords:
Partial similarity, reduced scale, buoyancy, ventilation

1 Introduction

Recreational tents can be considered as small buildings with two specificities: low thermal inertia and limited access to energy. In warm environments, thermal comfort is thus difficult to achieve, and rely mostly on the radiative properties of the textile envelope and on passive ventilation. Experimental development still remains the most reliable way to study internal comfort. Unfortunately, using large climatic wind tunnel is also very expensive and especially for tents having large dimensions. Therefore, tent designers and manufacturers may want to develop reduced scale approaches in order to reduce the experimental cost. However, from a scientific point of view, this approach is quite challenging, because when buoyancy and wind-driven ventilation are combined, not all similarity requirements can be met.

In the present contribution, a partial similarity approach is developed and then experimentally assessed on a classical family tent of moderate dimensions at full scale, and on its reduced scale model with a reduction ratio of 1/2. The family tent under investigation is 5.4m long, 1.85m high, and 2.3 m wide at full scale and is depicted in Figure 1. It is organized in one central living area, and two sleeping areas on its sides. The living area is equipped with one central door, the upper part of which is equipped with a so-called "window" made of an external mosquito net which can be either obturated ("closed") or apparent ("opened"). The opposite side of the living area is equipped with a similar closable mosquito net, facing the one on the door. As far as the sleeping areas are concerned, each one of them is enclosed inside an inner textile envelope protecting them from condensation occurring on the main roof of the tent. Each of the sleeping area is connected to the living area via a door with a permanent internal mosquito net on its upper part. Furthermore, the main roof on top of the sleeping areas is equipped on each side with two small external mosquito nets which are permanently opened. The reduced scale model is geometrically similar and was manufactured using the same textile fabric, and mosquito net porosity and with an overall 10% tolerance on its dimensions

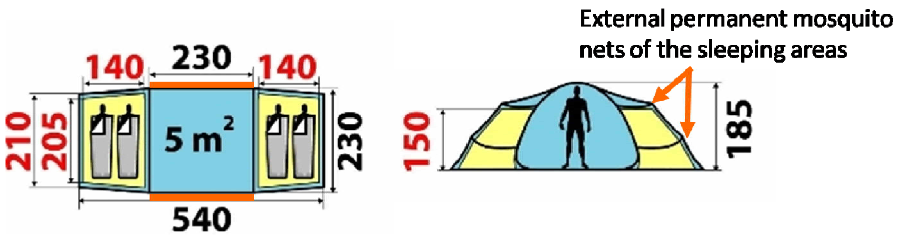

Figure 1 : *Description of the tent at full scale with one living area (blue) and two sleeping areas (yellow). The indicative position of the mosquito net is coloured in orange in living and sleeping area*

In the following, the partial similarity approach is first explained theoretically. Then, the experiments realized on both the full scale and the reduced scale tent models are described. Finally, the experimental results are presented and the validity of the similarity approach is analysed for each flow regime investigated.

2 Methodology : Similarity Approach

Two aspects need to be taken into account in the similarity approach. The first one concerns the forces in place in the volume (internal buoyancy effect) and the second concerns the orifices that enable the link between two environments: inside and outside.
Concerning the first one, the similarity, by assuming being under Boussinesq hypothesis, requires the conservation of both the Archimedes number (eq. 1) and the internal Reynolds number (eq. 2).

$$\left[\frac{gL_0\Delta\rho_0}{U_0^2\rho_0}\right]_{FS} = \left[\frac{gL_0\Delta\rho_0}{U_0^2\rho_0}\right]_{RS} \quad (1)$$

$$\left[\frac{U_0L_0}{\upsilon}\right]_{FS} = \left[\frac{U_0L_0}{\upsilon}\right]_{RS} \quad (2)$$

with g the gravity (m²/s), L a characteristic length (m), U the velocity (m/s), ρ the density (kg/m3) and υ the cinematic viscosity (m/s²). Subscripts *FS* and *RS* stand for full scale and reduced scale respectively.
The previous expressions imply, using the same fluid in both scales, the following scaling laws:

$$\left[\frac{L_0\Delta\rho_0}{U_0^2\rho_0}\right]_{FS} = \left[\frac{L_0\Delta\rho_0}{U_0^2\rho_0}\right]_{RS} \quad (3)$$

$$\left[\frac{U_{0,RS}}{U_{0,FS}}\right] = \left[\frac{L_{0,FS}}{L_{0,RS}}\right] \quad (4)$$

The requirement of having eq.(3) and eq. (4) both satisfied is very difficult to meet since the internal volume of the reduced scale model would then have to be $\left[(L_0)_{FS}/(L_0)_{RS}\right]^3$ hotter than the full scale model. Heating in such a way the internal volume would then lead to being out of the Boussinesq hypothesis even for the small reduction ratio (1/2) studied here [Etheridge (1996)]. In previous studies, buoyancy driven flows were thus studied using water as the working fluid and saline solution

to represent the heating sources [Fitzgerald (2010), *Kaye (2004)*, Linden (1990), among others]. These approaches are not suitable considering the complex tent geometry. Besides, studying strict similarity implies to reproduces similar boundary condition which is very challenging since even less possibilities are left concerning for example surface radiation heat transfers or local convection heat transfers.
An alternative approach is to use partial similarity in order to simulate at a reduced scale the mean natural buoyancy effect (or air column weight). If the aim is to focus on global variables such as the air change rate within the volume and global thermal stratification, the similarity on the internal Reynolds number is not required. Indeed, internal unventilated zone will not be catched but the main buoyancy effect through the air change rate and the thermal internal stratification can be reproduced. In this context, and using the same fluid for both sale and same external velocities, the above scaling law is reduced to:

$$[L_0 \Delta\rho_0]_{FS} = [L_0 \Delta\rho_0]_{RS} \Leftrightarrow [L_0 \Delta T_0]_{FS} = [L_0 \Delta T_0]_{RS} \qquad (5)$$

Using these assumptions, the similarity requirement is then satisfied by having the same air column weight in both scales (eq. 5). In our study, as the length scale reduction ratio is ½, this means having a mean thermal gradient on the reduced scale model twice as high as for the full scale.

The second aspect to consider while studying reduce scale model is the impact of length scale on orifice laws (airflow/pressure drop laws). The well known orifice equation, used in ventilation design, takes the following general form:

$$\Delta P = KQ^n \qquad (6)$$

with K a parameter that integrates the orifice area and the well known discharge coefficient C_d, ΔP the pressure drop of the orifice (Pa) and Q the volumetric air flow rate (m^3/s).
If in both scales, the same laws are used for each orifice and the same pressure drops are reproduced, the airflow rates will be directly linked to the orifice area ratio between both scales. This leads to the following relationship between airflow rates for both scales and therefore for air change rates (with V the volume (m^3) of the enclosure):

$$(Q)_{FS}/(Q)_{RS} = [(L_0)_{FS}/(L_0)_{RS}]^2 \quad ; \quad (Q/V)_{FS}/(Q/V)_{RS} = (L_0)_{RS}/(L_0)_{FS} \qquad (7)$$

In this study, the reduced scale model makes use of the same textile envelope and same mosquitoes for external openings. Therefore, eq. (5) and (7) are relevant for comparison between both scales.

3 Experiments

Both the full scale and the reduce-scale model (1/2) are investigated in a climatic wind-tunnel, so that the similarity hypothesis can hence be assessed experimentally. The measurements performed inside the tents are focused on global quantities: air change rate obtained with the tracer gas technique, and global air column weight (mean thermal gradient).

3.1 Climatic conditions and configurations tested

The measurements have been carried out in different sections of the climatic wind-tunnel (figure 1). In all cases, two different wind speeds have been investigated: 1m/s (for mix convection) and 4m/s (for forced convection). The full scale model has been investigated in the climatic section with ambient conditions reproducing typical summer conditions with an ambient air temperature regulated at 25°C, and a radiation on the solar spectrum of 630W/m^2 at the tent height (measured with a pyranometer). The reduced scale model has been studied in the dynamic section (not regulated in temperature) using

radiation from 6 heating resistance emitting mostly in the near-infrared. The radiation intensity on the reduced scale model has been tuned in order to get a similar air column weight as for the full scale model, meaning a mean thermal gradient twice bigger for the reduced scale model. This optimisation has been realized by changing the distance between the radiation source and the reduced scale tent.
Different ventilation regimes were tested, by varying the wind speed (1m/s or 4m/s), the wind orientation, and by closing or opening the living area mosquito nets. The wind speed of 1m/s was chosen to ensure the climatic wind-tunnel temperature regulation and to prevent a heat island effect on the reduced-scale model. However the air velocities inside the tent are lower than 1m/s due to the limited surface area of tent openings and to the pressure drop through the mosquito nets.
In the two wind-tunnels, the radiation sources illuminate a rectangular area on the ground, such that each tent model benefit from a rather homogenous radiation when the largest dimension of the tent is aligned with that of the radiation bench. In the climatic section, the radiation bench is oriented in the same direction as the wind (stream-wise orientation) whereas in the dynamic section it is oriented perpendicular to wind (span-wise direction). For mixed convection configurations (1m/s), it was assumed that the influence of radiation is more important than that of wind, and therefore the tent models were oriented in the same direction as their radiation bench : stream-wise for the full scale tent and span-wise for the reduced-scale tent.

3.2 Air change rate measurement

The air-change rate in volume/hour is measured using the same technique and equipment in the full scale and in the reduce scale model. When all the tent doors are closed, the tent is constituted of the three well-separated zones: 1 living area and 2 sleeping areas. Considering the sleeping area with its door closed as a single zone, the tracer gas technique described in Sherman (1990) is then applied. It is operated in the decay mode, using ethane (C_2H_6) as tracer gas. Thanks to its density close to that of Air (1.35kg/m^3), this gas is expected to follow faithfully the ventilation flow inside the measurement volume. Its concentration is measured using a COSMA analyser. The experimental setup is visible in Figure 2.

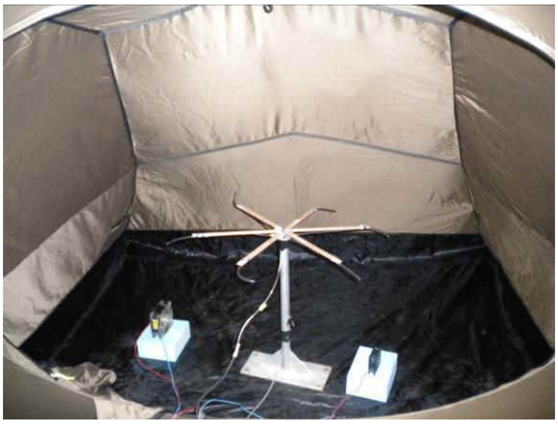

Figure 2: *experimental setup of the tracer gas technique in the sleeping area*

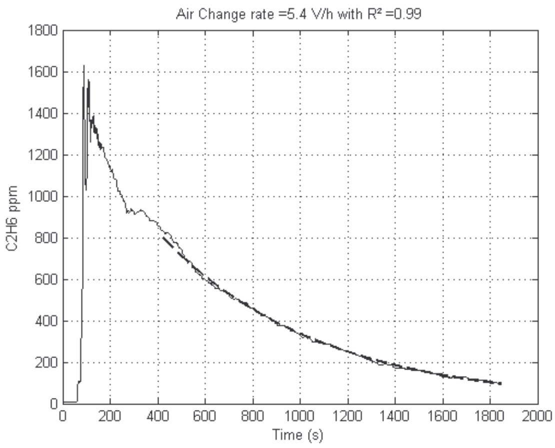

Figure 3: *Tracer concentration decay, with the fitting exponential.*

The gas is first injected and mixed inside the tent sleeping area using small fans. When a concentration above 1000ppm is reached, the injection and the mixing are stopped. The concentration inside the tent is assumed to be homogeneous when the injection is stopped. The air is then sampled at six different points inside the volume, and the tracer decay is recorded. The Air change rate is finally obtained by fitting an exponential function to the concentration evolution with time (Figure 3). A repeatability test has shown that the uncertainty is on the order of 10%. The position of sampling points was adapted to the internal volume of each tent model.

3.3 Mean thermal Gradient

In order to calculate the mean temperature thermal gradient ΔT_0 inside the tent, the air temperature distribution has been measured using an array of thermocouples of T-type distributed inside the tent. A calibration of the thermocouples has been performed using a calibration furnace and the temperature corrections realized on the thermocouples were less than 3%. For the full scale model, 55 thermocouples have been used (30 in the living area and 25 in the sleeping area). For the reduce scale-model, 23 thermocouples have been used (13 in the living area and 10 in the sleeping area). They are arranged in columns and their positions in the sleeping areas are given in Figure 4.

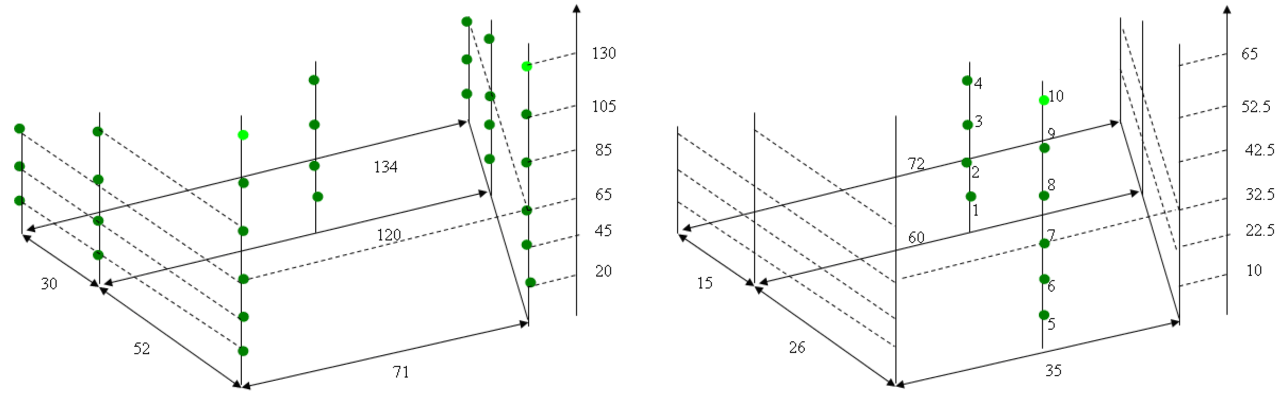

Figure 4 : *Position of the thermocouples in the sleeping area of the full scale model (left) and reduced scale model (right)*

The mean thermal gradient can then be calculated for each column using the following formulae:

$$dT = \frac{\sum_i (T_{i+1} - T_i)(H_{i+1} - H_i)}{(H_{end} - H_1)} \tag{8}$$

4 Results

In this section, the internal thermal stratification in the sleeping area and the living area is first presented for the full scale and the reduced scale tent models. Then, the air change rate values as a function of mean thermal gradients for the different configurations are presented and compared both scales.

4.1 Internal thermal stratification

The internal thermal stratification in both sleeping and living areas is presented in Figure 5 for the full-scale model and in Figure 6 for the reduced-scale model. In each figure, the results are given for both forced and mixed convection and considering mosquitoes either opened or closed. In the sleeping area of the full scale model, all thermocouples columns display similar results, and hence only the two columns equipped with the more numerous measurements points are shown. For the reduced scale model, only two thermocouples columns are used in the experimental setup (see Figure 4), and both of them are presented in Figure 6. As far as the living area of both scales is concerned, the results presented in Figure 5 and Figure 6 are those measured on the columns positioned at the centre of the alcove and its frontier with sleeping area.

In Figure 5, it can be seen that mixed convection presents strong thermal stratification with a constant evolution in the sleeping area and with a strong interface near 130cm and just above the mosquitoes for the configuration with closed and opened mosquitoes respectively. The configuration with opened mosquitoes only slightly reduces the mean thermal gradient within both models. For forced convection regime (for the span-wise wind incidence), thermal stratification is being negligible in both volumes and imply mixed ventilation within both sleeping and living areas.

Aside the impact of infra-red instead of solar spectrum heat flux, Figure 6 shows similar evolution of internal stratification for the four configurations studied (forced and mixed convection with mosquitoes opened and closed respectively). The forced convection implies mixed ventilation within both volumes independently of the mosquitoes being opened or closed. Mixed convection with infra-red heat flux implies very high surface temperature linked to a higher absorption coefficient in the infra-red spectrum. The highest temperature in the living room is obtained at 5cm below the alcove textile. The temperature exceeds external temperature up to 60°C. Nevertheless, strong stratification is visible on the curves for this convection regimes and the impact of opening mosquitoes is similar as for full scale.

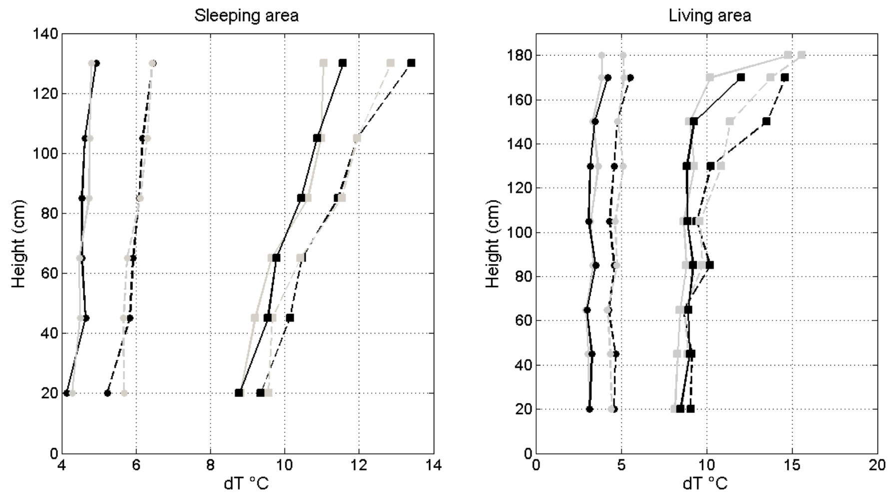

Figure 5 : *Thermal gradients within the sleeping area (left) and living area (right) for forced and mixed convection ('o' and '□' symbol respectively) for configuration with mosquitoes closed (doted line) and open (line) for the full scale model.*

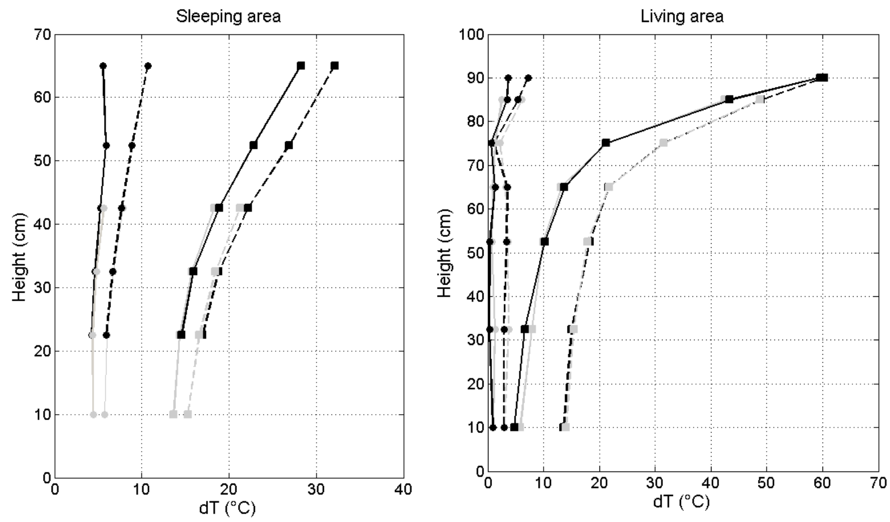

Figure 6 : *Thermal gradients within the sleeping area (left) and living area (right) for forced and mixed convection ('o' and '□' symbol respectively) for configuration with mosquitoes closed (doted line) and open (line) for the reduced scale model.*

These internal thermal stratification shows that the type of internal ventilation (mixed or displacement) is reproduced in both scale. The boundary conditions are strongly different due to the spectrum heat flux used. The reduced scale, with infra-red heat flux as radiation, present very high surface temperature and might therefore implies different behaviour in the global approach wanted in the study.

4.2 Air change rate as a function of mean thermal gradient

Air change rate measurement, with tracer gas technique, has been systemically done at both scales. The results are presented in Figure 7 as a function of the mean thermal gradient. In order to qualify the partial similarity approach used in this study, both models are presented in the same graph. Using equations (5) and (7), the results at reduced scale have been divided by the length scale reduction used (e.g. for reduced scale $dT = dT_{measured} / 2$ and $Ach = Ach_{measured} / 2$).

Several configurations are presented in Figure 7, depending on the type of convection (mixed or forced), on the wind incidence for forced convection and on whether the tent openings are opened or closed. For forced convection, the wind incidence has a strong impact on the air change rate, but a limited one on thermal stratification (mean gradients are already small in forced convection, the impact is thus limited regarding absolute values). Considering mixed convection, the radiation is the most important parameter. Therefore, results are presented considering orientation with regards to the wind direction for the forced convection (thus, 2 wind incidences) and with regards to the radiation bench orientation for the mixed convection regimes (only one orientation retains disregarding the wind incidence).

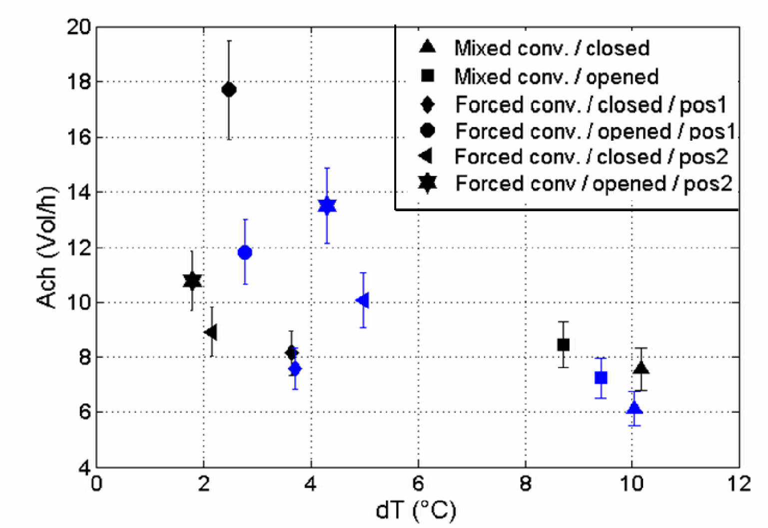

Figure 7 : *Representation of air change rate (Ach) measured on both scales. Same symbol are used for each configuration, blue colour is used for the full scale model and black colour for the reduced scale model. In the legend, 'conv' stands for convection, pos1 to a stream-wise position of the tent and pos2 to a span-wise position of the tent*

Figure 7 shows similar results for the two configurations in mixed convection regimes (□ and Δ symbols) at both scales. Results concerning forced convection are less accurate depending on the orientation. Indeed, some encouraging results in forced convection are obtained for the tent in position 1 (wind incidence toward the door: span-wise incidence) with closed mosquitoes. On the contrary, strong discrepancies are observed in forced convection for the three other configurations: with opened and closed mosquitoes for position 2 (wind incidence toward the sleeping area: stream-wise incidence) and with opened mosquitoes for position 1. Some Reynolds effect might be dominant, for these cases, within the sleeping volume. Considering position 2, some permanent openings in the sleeping area, directly exposed to wind, probably lead to sort of wind corridor effects within the volume for both configurations (opened or closed mosquitoes). Considering position 1, these permanent openings are positioned on the sides and are thus less influenced by wind (pressure coefficient are lower on the side than for front surfaces), leading to different effects for both configurations with opened and closed mosquitoes. These three cases are clearly not well reproduced using partial similarity, and would have required the conservation of both the Reynolds and Archimedes numbers (full similarity). However, the similarity equations given in the first section show that this would result in a considerable heating of the reduced scale model breaking up the Boussinesq assumption.

Finally, the partial similarity approach employed is focused on the buoyancy effect and accordingly some encouraging results are obtained for configurations being mainly influence by the buoyancy effect:

- mixed convection for both opened and closed living area mosquitoes
- forced convection with closed mosquitoes in the living area and with a wind incidence such that the sleeping area permanent openings are not directly exposed to wind (position 1).

The results are not so good for configurations for which wind effect is stronger than buoyancy effect:

- forced convection with a wind incidence directed toward the permanent opening of the sleeping area (position 2)
- configurations with opened mosquitoes in the living area configuration for all wind directions

5 Conclusion

A partial similarity approach was derived and used to study buoyancy driven and wind-driven ventilation inside a reduced-scale tent model. The partial similarity approach is based on the conservation of the internal Archimedes number (and hence of the global air column weight) and of the volumetric flow rate through the openings.
This approach is then investigated experimentally through the measurement of the air-change rate and mean thermal gradient inside a full-scale tent model and a geometrically similar reduced-scale tent model (with a reduction ratio of ½). Different ventilation configurations are studied, by varying the wind-speed (1m/s and 4m/s), the wind orientation, and by opening or closing some mosquito net.
The analysis and comparison of the air change rate as a function of the thermal gradient for the full-scale and the reduced-scale models show that the partial similarity approach is relevant for configurations being mainly influence by the buoyancy effect: mixed convection, and in forced convection with configurations minimizing the air inlet through the tent openings. On the contrary, the approach does not seem appropriate for configurations for which wind effect is stronger than buoyancy effect (forced convection with openings favourable to air inlets).
Finally, this approach is thus found to be adapted for the study of passive ventilation in tent in summer-like conditions with low external wind, which represents the most severe condition for tent users and is therefore of primary interest for tent designers and manufacturers.

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6 References

Etheridge D. and Sandberg M., *Building Ventilation, Theory and Measurement*, Ed. Wiley, 1996

Kaye N. B. and Hunt G. R. *Time-dependent flows in an emptying filling box* J. Fluid Mech. (2004), vol. 520, pp. 135–156

Linden P. F., Lane-Serff G. F. and Smeed D. A. , *Emptying filling boxes : the fluid mechanics of natural ventilation* J . Fluid Mech., 1990, vol. 212, p p . 309-335

Fitzgerald S.D., Woods A.W., *Transient natural ventilation of a space with localised heating*, Building and Environment 45, 2010, p.p. 2778-2789

Sherman M.H., *Tracer-gas techniques for measuring ventilation in a single zone*, Building and Environnement, 1990, vol 25:4, p.365-374