393: An air circulation comparative study between the application of short and long wind-catchers in a confined space: case of House VI of "Vila" 37

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Abstract

In Vila 37 – in the Catete neighbourhood in Rio de Janeiro city – the houses had to grow vertically as the original project did not contemplate the space around the houses. The continuous urban transformation process, as well as the changes which took place in the houses themselves, interfered in the ventilation quality in those buildings. The project of the House VI, in Vila 37, was checked, as its ventilation was restricted to the windows in the facade. In a previous study we tested the application of a long wind-catch that crosses all the construction. The results obtained, encouraged us to test the introduction of a short wind-catch with openings only on the third-floor. This pavement indeed suffers more heating during the day because of solar radiation. Computational simulations are carried out aiming to evaluate ventilation changes. The air circulation problem was solved by using a mixed stabilized finite element method applied to the full Navier-Stokes equations. The results obtained are compared with the original situation (without wind-catch) and with the scenario tested previously. These results suggest that the wind-catch use deserves more attention and research. They show an improvement of the ventilation besides the reduction of environmental and economical costs.

Keywords: sustainable solutions, passive ventilation system, computational modelling, wind-catch, finite element method

1. Introduction

At the end of the 19th century the urban population in Rio de Janeiro city reached increased intensely. This new profile impelled the city towards its suburbs and the construction of homes for all of the social classes. Houses like those ones of Vila[1] 37 were built for every city. They were small houses that usually served for the working class. This specific vila was built in the year 1890 by Mr. Manuel Marinho da Silva.

Across the years the occupation of the ground was altered as was previsible in every direction. So a lot of constructions in old areas of the city were demolished giving place to new and taller buildings. The enlargement of streets and the creation of new areas as Flamengo Beach and its embankment almost transformed the covering of the city completely.

In Vila 37 –in the Catete neighbourhood in Rio de Janeiro city – the houses had to grow vertically as the original project did not consider the space around the houses, see Fig. 1. The continuous urban transformation process, as well as the changes which took place in the houses themselves, interfered in the quality of ventilation in those buildings which were swallowed by the urban volumes. Aiming to analyze the changes which took place in the ventilation of these confined spaces, the project of the house number VI in Vila 37 was checked, as its ventilation was restricted to the windows in the facade.

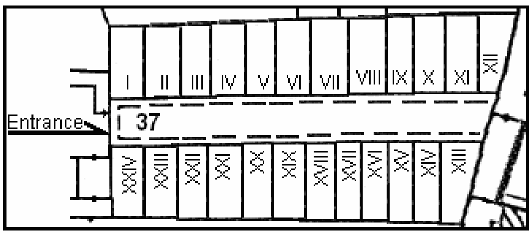

Fig 1. The site plan of the whole area (1995) - Secretaria Municipal de Urbanismo (Urbanization District Secretariat) of Rio de Janeiro City.

In Fig. 2, the plans of the three floors and the façade can be observed and in Fig. 3, the sections of House VI can be observed. These sketches are reproductions of the originals from August, 2000, regarding the last suffered increment for construction. Actually these sketches are archieved in the Secretaria Municipal de Urbanismo (Urbanization District Secretariat - Division of Property and Constructions Bureau) of Rio de Janeiro City.

Naturally ventilated environments have thermal conditions directly related to the air circulation and the characteristics of the built environment. In Drach [1] and in Drach and Karam [2], we tested the use of wind-catchers adopting works of the Egyptian architect Hassan Fathy [3] that

[1] A "vila" in Brazil is a small private cul-de-sac with terraced houses which share a common area and entrance gate.

obtained important results starting from the use of these ingenious mechanisms.

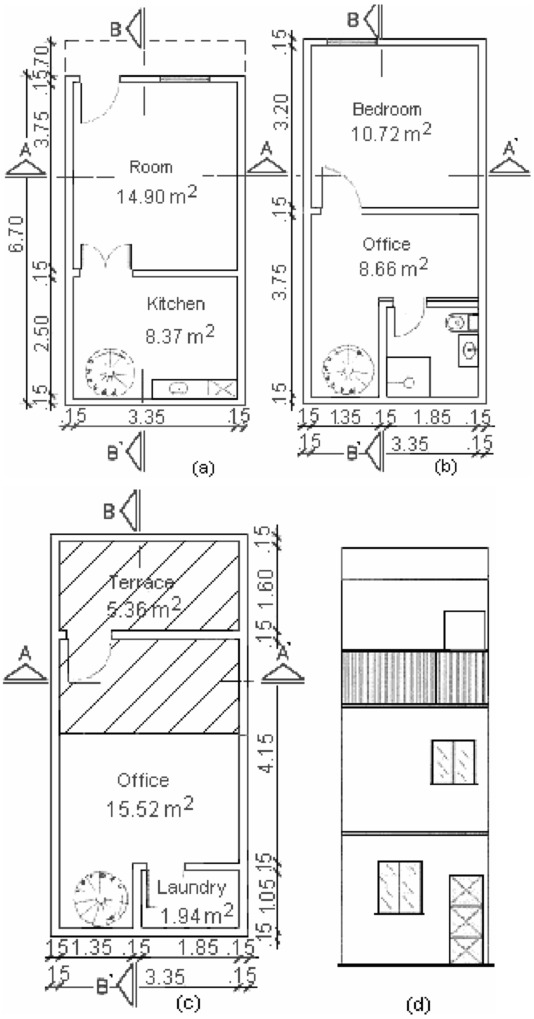

Fig 2. Plans of the first-floor (a), the second-floor (b), the third-floor (c) and the facade (d).

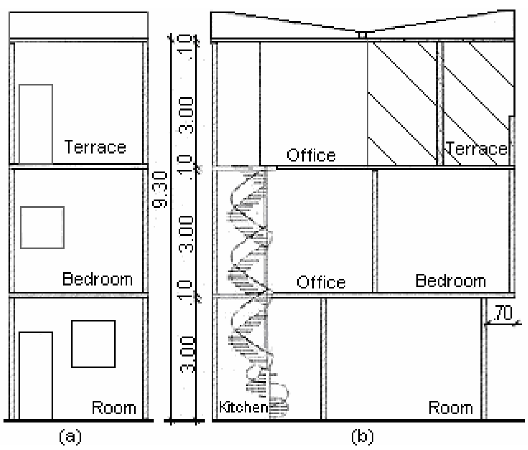

Fig 3. Sections AA (a) and BB (b).

To ventilate the indoor of a construction it should be known where to put the openings to obtain a cross ventilation [4]. In specific case of Vila 37, aiming to increase the ventilation, in a previous study we tested the application of a long wind-catch that crosses the entire construction and has openings on all of the floors. The results obtained allowed us to conclude that the adoption of this passive ventilation system was able to alter the indoor wind field pattern substantially and to promote an increase in the ventilation. So we will encourage testing the introduction of a short wind-catch that has openings only on the third floor. This is the pavement that indeed suffers grater heating during the day due to more contact with solar radiation. This is due to the fact of this shorter type of wind-catch being of much simpler executability and economical construction.

In an attempt to increase and promote better ventilation, simulations using wind-catch will be carried out. The analysis starts by solving the air circulation problem to determine the wind fields, using a mixed stabilized finite element method applied to the full Navier-Stokes equations written in velocity and pressure variables. The results obtained are compared with the computational simulation results of the original situation so as to be without wind-catch and of the two new scenarios; with long wind-catch and with short wind-catch.

The presentation of results is focused on the interior of the house because it is our region of interest and requires better cooling, here induced by the ventilation. Through the results of computational simulations we can observe that the use of wind-catch allied with an appropriate plan of openings shows an improvement of air circulation. These passive strategies seem to present a potential to provide better ventilation and air quality in addiction to the fact of aiding in the reduction of environmental and economical costs.

2. Mathematical Formulation

The analyses start by solving the air circulation problems to determine the wind fields, using a mixed stabilized finite element method, like Petrov-Galerkin [5], applied to the full Navier-Stokes equations written in velocity and pressure variables [6].

The problem of air circulation can be modelled through mass and momentum conservation equations. Assuming incompressibility, the mathematical formulation for the general problem can be written as: Find $\mathbf{u}$ and p satisfying the following system,

$$div\ (\mathbf{u}) = 0, \text{ in } \Omega \times [0, \mathrm{T}], \tag{1}$$

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\nabla \mathbf{u})\mathbf{u} - 2\mu\ div\ \varepsilon(\mathbf{u}) + \nabla p = 0, \text{ in } \Omega \times [0, \mathrm{T}], \tag{2}$$

with initial and boundary conditions,

$\nabla(\mathbf{u}).\vec{\mathbf{n}} = 0$ in $\Gamma_v \times [0,\mathrm{T}]$, $\mathbf{u}(\mathbf{x},t) = \bar{\mathbf{u}}(\mathbf{x},t)$ in $\Gamma_u \times [0,\mathrm{T}]$ and $\mathbf{u}(\mathbf{x},0) = \mathbf{u}_0$

where: $\mathbf{u} = \mathbf{u}(\mathbf{x},t)$ is the velocity vector, $p=(\mathbf{x},t)$ is the pressure, μ is the viscosity, ρ is the density, $\vec{\mathbf{n}}$ is the normal vector, $\varepsilon(\mathbf{u}) = \frac{1}{2}\left(\nabla\mathbf{u} + \nabla\mathbf{u}^T\right)$, Ω is the bounded domain with boundary $\Gamma = \Gamma_v \cup \Gamma_u$ and the time $t \in [0,\mathrm{T}]$.

3. Methods

The numerical solutions are here obtained by a stabilized mixed finite element method that allows us to deal with the problems that come from the equation system. The first problem is the difficulty in constructing approximation spaces for problems with internal constraint. The second is the non-linear nature of the convective type and the last one is the challenge of dealing with numerical instabilities when advection effects are dominant. Here, a Petrov-Galerkin type method was implemented and applied to analyze indoor air circulation cases, ensuring stability for dominant advection and for internal constraint.

Being L^2 and H^1 the usual Hilbert spaces and R_l^h the Lagrange polynomial space of the degree l and class C^0. Then, defining the following approximation spaces

$$V_h = \{\mathbf{u}_h \in (H_0^1(\Omega) \cap R_l^h(\Omega))^2, \mathbf{u}_h(\mathbf{x},t) = \bar{\mathbf{u}}_h(\mathbf{x},t) \text{ in } \Gamma_u\}$$

$$V_h \subset (H^1(\Omega))^2$$

$$V_h^0 = \{\mathbf{v}_h \in (H_0^1(\Omega) \cap R_l^h(\Omega))^2, \mathbf{v}_h(\mathbf{x},t) = 0 \text{ in } \Gamma_u\}$$

$$V_h^0 \subset (H^1(\Omega))^2$$

$$P^h = \{p_h \in (L^2(\Omega) \cap R_l^h(\Omega)); \int_\Omega p_h \partial\Omega = 0\} \subset (L^2(\Omega))$$

With the usual norm

$\|\mathbf{u}\|_1^2 = \|\mathbf{u}\|_0^2 + \|\nabla \mathbf{u}\|_0^2$ of H^1 and $\|p\| = \|p\|_0$ of L^2.

The wind field can be determined by solving the following formulation:

Find $\{\mathbf{u}^h, p^h\} \in V^h \times P^h$ satisfying the following system

$$B\,(\mathbf{u}_h, p_h;\, \mathbf{v}_h, q_h) = 0,\ \forall\ (\mathbf{v}_h, q_h) \in V_h^0 \times P_h \text{ where:}$$

$$\begin{aligned}
B\,(\mathbf{u}_h, p_h;\, \mathbf{v}_h, q_h) &= \left(\frac{\partial \mathbf{u}_h}{\partial t}, \mathbf{v}_h\right) + \left((\nabla \mathbf{u}_h)\,\mathbf{a}_h, \mathbf{v}_h\right) + \\
& 2\nu\left(\varepsilon(\mathbf{u}_h), \varepsilon(\mathbf{v}_h)\right) - \left(p_h, div(\mathbf{v}_h)\right) + \left(q_h, div(\mathbf{u}_h)\right) + \\
& \left(div(\mathbf{u}_h), \delta_2 div(\mathbf{v}_h)\right) + \\
& \delta_1 \sum_{e=1}^{Nel} \left(\frac{\partial \mathbf{u}_h}{\partial t} + (\nabla \mathbf{u}_h)\,\mathbf{a}_h - 2\nu\ div\ \varepsilon(\mathbf{u}_h) + \nabla p_h,\right. \\
& \left.\left((\nabla \mathbf{v}_h)\,\mathbf{a}_h - 2\nu\ div\ \varepsilon(\mathbf{v}_h) + \nabla q_h\right)\right)_h + \gamma\,(p_h, q_h),
\end{aligned}$$

$$\forall\ \mathbf{v}_h \in V_h^0 \text{ and } q_h \in P_h.$$

where ν is the air viscosity. With $\gamma << 1$ and δ_1 and δ_2 stabilized parameters suggested by Franca and Frey [6].

4. Simulations

We imposed some changes to the original project of House VI by adding a wind catch. Firstly it was a long pipe that crosses the whole construction and it has openings in all of the floors. Secondly was a short pipe that has openings only on the third-floor. The space of the access stairway to the floors stays open so it is aiding ventilation. The sketches of the three new scenarios: the original project, the project with a long wind-catch and the project with a short wind-catch (Fig. 4).

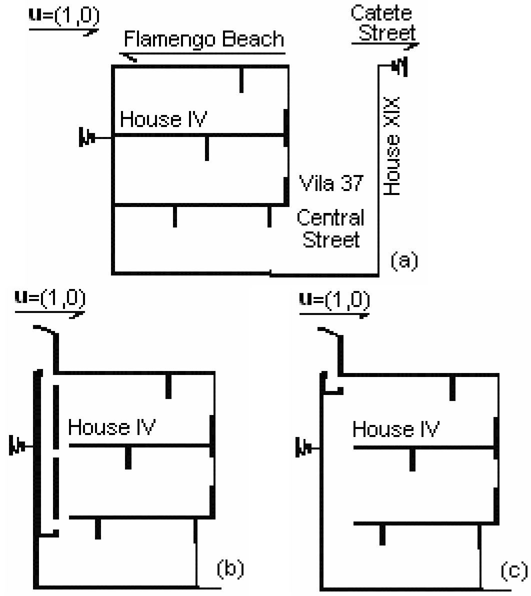

Fig 4. Original project (a), project with long wind-catch (b) and project with short wind-catch (c).

Arrows in sketch figures indicate the direction and intensity of the outside wind, providing the boundary conditions to the air circulation problem. The absolute value of 1 m/s was adopted for the outside wind. This value adopted was low because we had the intention of observing whether subtle outdoor ventilation would or not interfere with the indoor environment. According to the Beaufort scale, used in time forecast, this value corresponds to breeze without wind perception.

The whole meshes comprise areas bigger than the areas of the plans (Fig. 5) in order to impose boundary conditions on their borders and to leave unknown the velocities at the indoor areas entrances that are determined by the solution of the problem.

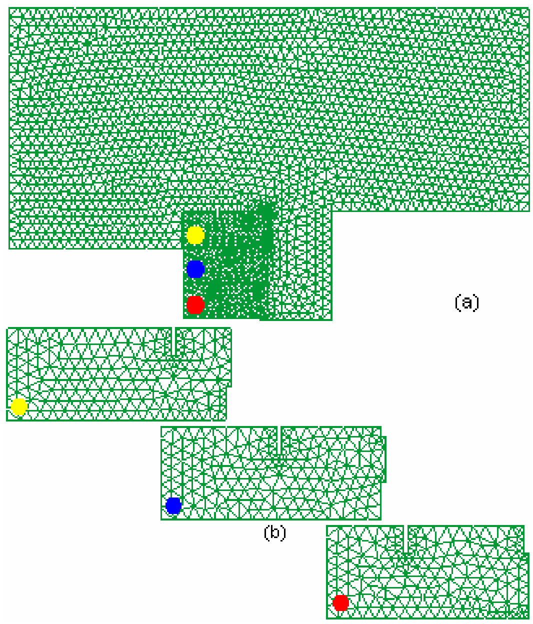

Fig 5. Original project whole mesh (a) and its mesh details (b).

The details of the meshes generate for the two new scenarios can be see in Fig. 6.

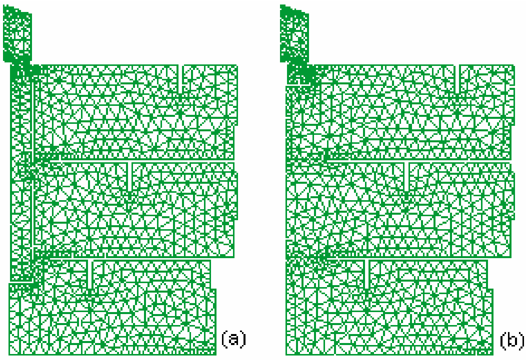

Fig 6. Mesh detail of the projects with long wind-catch (a) and with short wind-catch (b).

5. Results

As we stated previously, the presentation of the results is focused on the interior of the house. In order to compare the alterations made to the original project change, the same colour scale was adopted to show the results, in other words, including the same wind strip. These results were taken in terms of contour fill of |**u**| in a scale in which the darkest colour will be adopted for superior velocities of 1.5 m/s in the colour scale (Fig. 7(a), 7(b) and 7(c)).

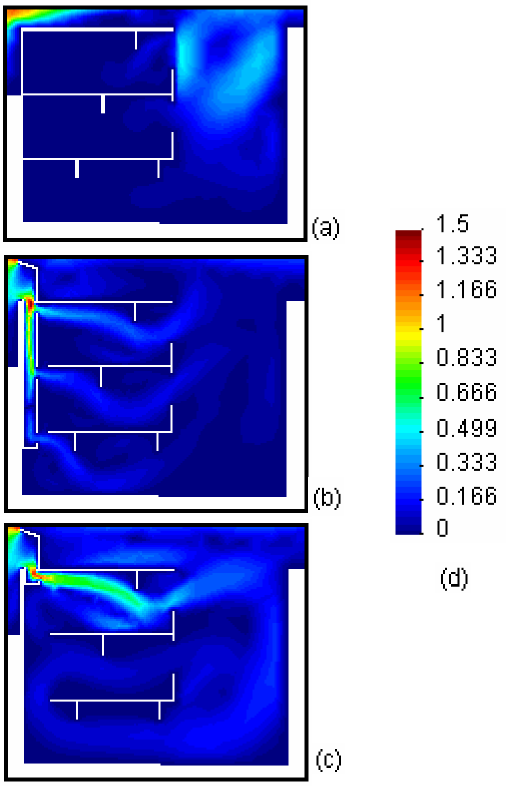

*Fig 7. Contour fill of |**u**|. Original project (a), long wind-catch (b), short wind-catch (c) and colour scale (d).*

For a more detailed view of indoor air circulation, the results were also presented in two scales with a reduced superior value in relation to the one presented previously, in other words, the darkest colour will be adopted for superior velocities to 1.0 m/s (Fig. 8(a), 8(b) and 8(c)) and 0.5 m/s (Fig. 9(a), (b) and 9(c)) in the colour scale.

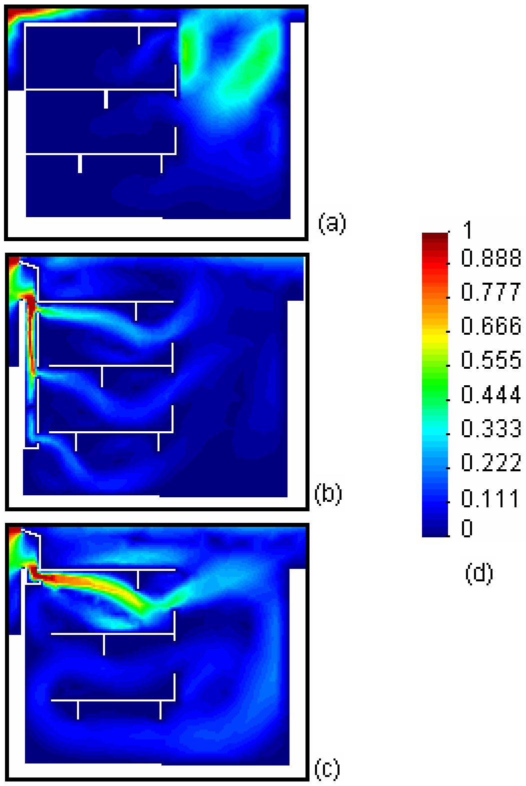

*Fig 8. Contour fill of |**u**|. Original project (a), long wind-catch (b), short wind-catch (c) and colour scale (d).*

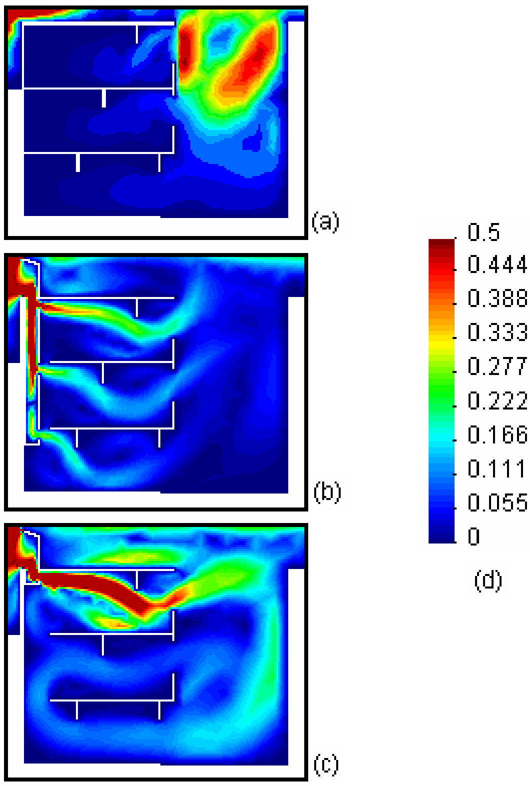

*Fig 9. Contour fill of |**u**|. Original project (a), long wind-catch (b), short wind-catch (c) and colour scale (d).*

We can observe from Fig. 7(a), which represents the wind fields of the original project, that the indoor environment presents the poorest ventilation if we compare the results presented in Fig. 7(b) and Fig. 7(c). The results obtained without the existence of the wind-catch for the three colour scales of contour fill of |**u**| (Fig. 7(a), 8(a) and 9(a)) allow us to see that indoor velocities higher than 0.1 m/s can not be observed.
The two new scenarios here proposed, were able to produce an improvement in terms of ventilation even when the external wind was low (1m/s). It is possible to notice by comparing the three figures that the wind field patterns changed. Inside the three pavements the air circulation increases and it comprises almost all the rooms for the two new scenarios. For the case with long wind-catch the results obtained, for the three colour scales of contour fill of |**u**|, allow us to see that indoor velocities higher than 0.25 m/s can be observed in all the floors (Fig 9(b)). In the case with short wind-catch, in spite of the ventilation general increase, values of velocities higher than 0.25 m/s can be observed only on third-floor (Fig 9(c)).
The fact that the introduction of the wind-catch in both new scenarios has significantly altered the wind field suggests that its application deserves more investigation.
In Fig 10, 11 and 12 the results are presented in terms of velocity wind field. For a more comprehensive view of the indoor air circulation we selected an area (red square) to be enlarged.

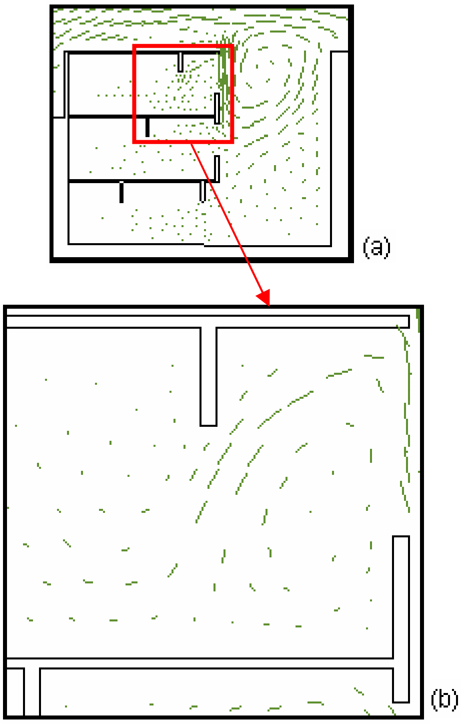

Fig 10. Detail of the velocity wind field of the original project (a) and a more detailed region (b).

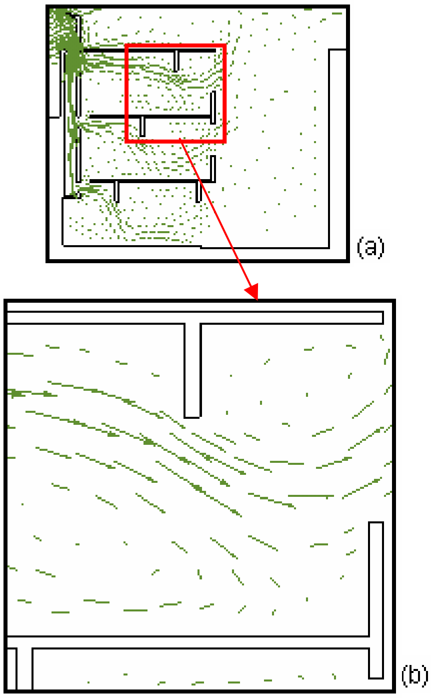

Fig 11. Detail of the velocity wind field of the long wind-catch project (a) and a more detailed region (b).

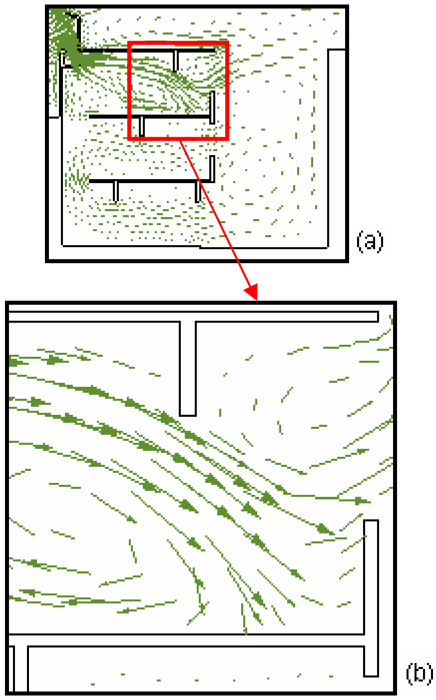

Fig 12. Detail of the velocity wind field of the short wind-catch project (a) and a more detailed region (b).

Regarding the velocity wind-fields resulting from the three scenarios it was possible to observe an improvement in the two new scenarios in terms of ventilation even when the external wind was low (1m/s). Changes in the wind field patterns can be see in the three figures and their details (Fig. 10, Fig. 11 and Fig. 12).
If our analysis was focused on interior of the house the results show an increase of the ventilation in all floors even when the short wind-

catch was applied. Focusing the interest only on third-floor it is possible to observe that with the long wind-catch the ventilation intensity is higher. So it will be a better choice because besides scarce ventilation this pavement receives solar radiation directly.

6. Conclusion

The studies of Evans [7] indicate the need to ventilate for comfort subjects, hygiene and health. In the case of Rio de Janeiro city these ventilation recommendations become even more pertinent, once this city is placed in a hot climate region.

The computational modelling becomes of great help and value in order to make possible the project configuration evaluations and the test of possible improvements, both in the pre-occupancy and in the post-occupancy phases.

Here, we tested the possibility of seeking improvements by introducing changes in the original project designs aiming at the comfort of built environments with low financial and environmental costs.

To analyze the air circulation problems, we used a mixed stabilized finite element method, like Petrov-Galerkin, which allows us to deal with the problems that come from the equation system. It ensures stability for dominant advection and for the internal constraint. The application of the finite element method for space discretization in studies related to architecture and a town plan, presents as an advantage the fact that it is efficient when working with domains of complex geometries as well as with varied boundary conditions. Through the use of this method it is possible to obtain punctual values of wind velocity, temperature and gas concentration in the areas of interest.

Regarding the original project, it is possible to notice the poor indoor ventilation in terms of distribution and intensity. We proposed changes to the original project through the introduction of the wind-catch in two ways. Firstly we added to a project a long wind-catch that crosses all the building with openings on all floors. Secondly we introduced a short wind-catch only on the third-floor. The computational experiments with both long wind-catch and short wind-catch brought positive results. It was possible to observe the increase in air circulation in terms of intensity and distribution.

The computational velocity results allow us to see the capacity of the system (wind-catch plus a studied arrangement of openings) to promote the indoor air circulation even when the outdoor wind is low, (1m/s). It also allows us to work with pre and post occupancy evaluation. These facts suggest that the utilization of wind-catch as well as optimal locations of openings are able to improve ambient conditions and they deserve more attention and research since these strategies show good potential in achieving significant quality still counting with the fact of being able to operate with reduced environmental and economical costs.

7. Acknowledgements

Patricia R. C. Drach, would like to thank the support of the National Council for Scientific and Technological Development (CNPq) and to thank National Laboratory for Scientific Computing (LNCC/MCT).

José Karam F. would like to thank the support of the project PRONEX/FAPERJ no. E-26/171.199/2003.

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