IMPACT OF DESIGN PARAMETERS ON THE NATURAL VENTILATION OF A FAMILY HOUSE ATTIC FROM SANTA FE (ARGENTINA)

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The roof of a family home introduces important amounts of heat into the house. In Santa Fe city (Argentina), the attic of social family houses is not designed with thermal optimization purposes. In this work, a low Reynolds number k-e turbulent model is computationally implemented to show that a proper selection of constructive parameters of a vented attic leads to a great reduction of the heat transferred from the roof to the ceiling. The main physical consequence of a vented attic is the existence of a convective flow barrier close to the roof that carries important amounts of heat from the attic out to the environment. It is shown that the heat transferred through the ceiling to the interior of the house can be reduced in more than 70 % for summer conditions. Roof pitch and attic volume are also explored.

Keywords: vented attic, computer fluid dynamic, buoyancy flow.

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I. INTRODUCTION

A family home roof is usually the component that transfers more heat than any other wall of the house. Consequently, most design building codes suggest passive ventilation as an alternative to produce important energy savings, i.e., the International Residential Code [1] demands attics ventilation unless local codes state the contrary, generally due to atmospheric or climatic conditions.

Most attics of social family houses in Argentina are built without connections to the exterior. In some cases, only ventilation grills are used to allow pressure homogenization with external environment and to evacuate moisture, but the vent size, position, and orientation are not specifically designed to generate an important flow rate. Passive cooling isn't recommended by any national building code and is rarely implemented in local government social houses programs. The advantages and disadvantages of the application of attic ventilation compared to the traditional closed attic need to be evaluated using local climate data bases before recommending it as requirement in model house schemes [2]. Therefore, the impact of natural convection airflow on the heating load and its relationship with standard construction parameters (roof inclination angle, air gap cavity volume, etc.) can offer helpful information for sustainable roof design, especially in hot climate zones like Santa Fe city (Argentina) with temperatures that can exceed 43ºC. In this work, a trapezoidal-shaped cavity is used to describe the geometry of a single pitch roof attic. This geometry allows the possibility to study different roof pitches yet maintaining the attic volume constant and vice versa [3].

Recent works [4] have proved Computer Fluid Dynamics (CFD) as a valuable tool to estimate the impact of attic ventilation in roof thermal performance. Wang et al. [5] studied the natural convection effects on vented attics performance under winter conditions employing a two-dimensional steady-state finite volume model on a triangular air cavity by changing the vent size, ambient air temperature and ceiling insulation. On later papers, Wang and Shen [6, 7] employed a 2D unsteady CFD model assuming a mid-plane symmetry to study the impacts of ventilation ratio, vent balance and roof pitch on air flow and heating load of both sealed and vented attic for summer conditions. Recently, Iffa and Tariku [8] studied the effects on temperature profile and airflow patterns inside the cavity by varying the gap size between roof sheathing and ceiling insulation and the location of the vent area under both summer and winter conditions. The same authors used transient boundary conditions [9] to study the dynamic response of the roof thermal performance. All mentioned works showed the benefits of a vented attic in reducing the cooling loads, but they were mostly based on strict building codes guidelines and focused mostly in the vent size influence on the thermal performance, minimizing the importance of other constructive parameters that could improve the thermal performance of the attic of social homes of our zone.

The aim of this work is to obtain basic guidelines for selecting a few construction parameters that can optimize the attic thermal performance, i.e. vent openings size, attic volume and roof pitch. The turbulent air flow and natural convection heat transfer inside the attic are modeled in terms of the low Reynolds number $k-\varepsilon$ turbulent model which is validated using both experimental and numerical works.

II. MATHEMATICAL MODEL AND NUMERICAL TECHNIQUE

Fig. 1 sketches the typical parts of a single pitch roof that usually cover a low-cost family house, where thermal loads and the proposed vent openings on the front and back walls are shown. The air cavity is bounded by the inclined roof, the ceiling and the walls. The high temperatures of air and

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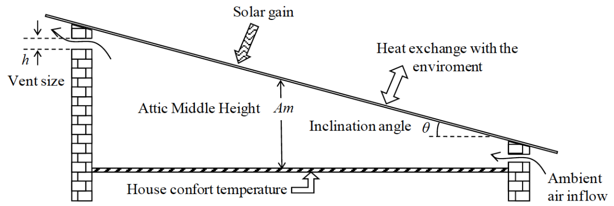

FIG. 1: Low-cost family house vented shed roof (attic), with thermals loads scheme.

solar radiation that impact on the roof, are transmitted to the house indoor passing through this cavity. The received thermal load will be considered as the combined effect of both solar radiation and heat exchange by natural convection between the roof and the environment. The front and back walls are assumed adiabatic (we neglect the heat flow through these walls). The ceiling consists of a thin covering material with negligible thermal resistance; therefore, we assume that it has the same temperature as that inside the house. The attic is located on a square room of 4 m long each side. The set of governing equations for natural convection turbulent flow is given by the Reynolds-averaged Navier-Stokes (RANS) equations of continuity (1), momentum (2) and thermal energy (3):

$$\nabla \cdot (\rho u) = 0 \tag{1}$$

$$\begin{aligned}(u \cdot \nabla)u = \nabla \cdot [-PI + (\mu + \mu_T)(\nabla u + (\nabla u)^T) \\ -\frac{2}{3}(\mu + \mu_T)(\nabla \cdot u)I - \frac{2}{3}\rho k I] + (\rho - \rho_0)g\end{aligned} \tag{2}$$

$$\rho C_p u \cdot \nabla T = \nabla \cdot (\lambda \nabla T) \tag{3}$$

where u is the velocity field vector, ρ the temperature dependent air density, ρ_0 the air density evaluated at a reference temperature (ambient), P the pressure, g the gravity acceleration field, μ the air dynamic viscosity, μ_T the eddy viscosity, k the turbulent kinetic energy, C_p the air heat value, λ the air thermal conductivity and T the temperature field.

The low Reynolds number $k-\varepsilon$ turbulence model employed in this work is a modification of the well-known $k-\varepsilon$ model, widely used in analyzing ventilation flow inside houses and buildings [10]. The model introduces two additional transport equations and two dependent variables: the turbulent kinetic energy, k, and the turbulent dissipation rate ε to the above RANS equations [11]. In order to describe the flow in the wall region, where viscous effects dominate, the employed low Reynolds number $k-\varepsilon$ model adapts the turbulence transport equations with the AKN (initials of its developers: Abe, Kondoh and Nagano) model [12] by introducing damping functions.

The equations system was solved using the Non-Isothermal Turbulent Flow module of the commercial finite element software COMSOL Multiphysics 4.4. To have a good convergence scheme, the solutions were obtained by following two steps: in the first step, the viscosity was set to a value approximately 10 times higher than the expected physical viscosity inside the attic, in the second step, the actual physical viscosity is calculated using the first step result as initial guess.

The nonlinearity introduced by the Navier-Stokes (RANS) and turbulence transport equations were solved using a segregated approach [13]: Navier-Stokes equations in one group and the turbulence transport equations in another. For each iteration of the Navier-Stokes group, three iterations for the turbulence transport equations were needed. A pseudo-time stepping approach was used to obtain steady state solutions.

III. RESULTS AND DISCUSSION

Model validation

The Numerical model was validated with Ampofo and Karaviannis [14] experimental measurements, who studied the low turbulence air flux driven by natural convection inside a closed cavity of square cross section (0.75 m each side), under a temperature gradient of 40 K between the lateral walls (323 K on the left wall and 283 K on the right one), with insulated top and bottom walls. The cavity was deep enough (1.5 m) to assure a 2D flux at any cross section far from anterior and posterior walls. Velocity and temperature profiles of moving air were measured at different positions in a cross section placed at the middle distance between anterior and posterior walls. Our numerical results show good agreement with experimental measurements (see Fig. 2). Moreover, the agreement between the temperature profiles is very precise in the boundary layer region where heat fluxes need to be computed in this work.

The model was also validated with the numerical work by Wang et al. [5], who developed a V2f turbulent model to analyze the buoyancy-driven air flux inside a vented attic of triangular shape, under a temperature gradient of 20 K between the base and the inclined top side, for winter conditions. The geometry of the 2D triangular cross section of the attic was 8 m long in the base and had a roof inclination ratio of 5/11. The streamlines and isotherms predictions obtained with our model reproduce the same behavior, especially for the case of a vented attic with 2 cm openings width and a R-20 insulation type for a 267 K ambient temperature. But the best agreement is observed when comparing two variables relevant for our study at summer conditions: heat transferred through the ceiling (HTTC) and mass flow. The HTTC predicted by Wang et al. [6] is 48.5 W/m while ours is 46.8 W/m, computing a percentage difference of about 3.5 %, while the mass flow difference between both models is about 1 % (0.0236 kg/s for Wang's model and 0.0238 kg/s for our model).

Summer boundary condition: Roof constant temperature vs solar radiation.

The influence of geometric dimensions on the attic thermal performance is very dependent on the thermal boundary conditions. A 295.15 K temperature is desired to have a comfortable indoor environment, being this the prescribed temperature on the ceiling. But it is not fully understood what types of thermal conditions can mimic the real roof conditions for any situation.

For winter conditions and snowfall zones, constant roof

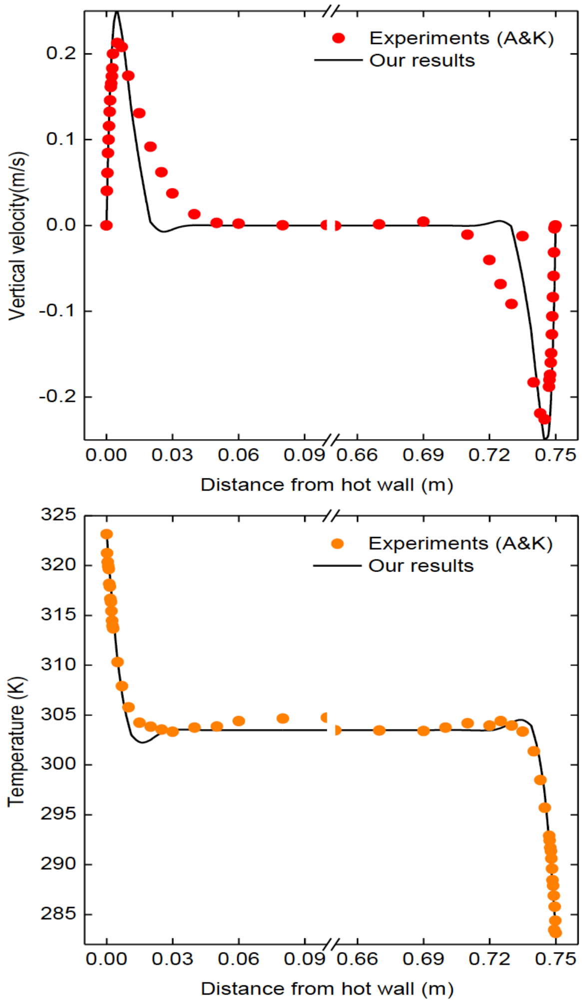

FIG. 2: Comparison of the present model results and experimental measurements made by Ampofo and Karaviannis14. Red: Vertical velocity. Orange: Temperature.

temperature is an appropriate condition since snow accumulation imposes its temperature and insulates the roof from outside atmosphere. For summer conditions, the roof is exposed to sun radiation, different ambient air temperature and convective dissipation, so it is not clear which roof temperature should be used as a boundary condition. For this reason, we compared two cases: **a)** a prescribed constant roof temperature (CRT), used widely in the literature [5-8] and **b)** a prescribed constant solar radiation (CSR) coupled to convective heat exchange with external environment. For both cases, a closed cavity without conection with exterior is used.

The value of 345.15 K was used for the CRT, as a typical summer roof temperature [6]. For the CSR case both solar radiation (heat flux) of 1000 W/m^2 and a convective heat flux from the Non-Isothermal Turbulent Flow module of COMSOL was used under different summer air temperatures.

Table 1 compares the HTTC between CRT and CSR for a varying ambient temperature and summarizes the absolute percentage differences (APD) between them. It can be noted that the APD minimum difference is computed for 305.15 K, and can be as greater as 22.5 %. This means that

TABLE 1: Constant roof temperature and constant solar radiation results comparison for summer conditions.

Ambient Temperature (K)		**Roof Average Temperature (K)**	**Heat transfer to the ceiling (MW/m)**	**Absolute percentage difference (APD) (%)**
CRT Case		345.15	65.6	-
CSR	300.15	340.75	55.3	15.8
	305.15	345.47	64.6	1.5
	310.15	350.99	72.0	9.7
	315.15	355.51	80.3	22.5

prescribing a constant roof temperature with a single value could not be an appropriate boundary condition for different ambient scenarios. The roof temperature will be hardly constant during summer for a wide ambient temperature variation and it is expected that the attic thermal performance will depend on the heat dissipation due to atmosphere conditions changes.

Radiation values are known from daily weather reports and convective coefficient can be easily obtained from bibliography, but roof temperature is not always known. Moreover, for vented configurations, the air exchange between the attic and the atmosphere could affect the average roof temperature due to an increased heat exchange by convection. Thus, the following results were obtained using radiation and convective exchange as the roof thermal boundary conditions.

Open vs closed cavity

In this section, we compare the HTTC between open (vented, see Fig. 1) and closed attic. For a 2D analysis, it is assumed that the openings go through the entire thickness of the walls. In this section, a constant height (vent size, see Fig. 1) of 5 cm is selected for the openings. Comparison is made for a proposed ambient temperature range corresponding to a hot summer day. As Fig. 3 shows, a constant HTTC difference between open and closed attic can be observed for the full ambient temperature range (Table 2). This difference is about 43 W/m for the selected opening height and is an important reduction of heat that does not enter the house. It can be noted that the HTTC increases with the ambient temperature for any case. However, for the highest ambient temperature (315.15 K), the computed HTTC for the vented attic is 50 % lower than that for the closed attic. The lower the heat transferred through the ceiling, the lower the energy needed to maintain a comfortable indoor temperature.

Air flow streamlines inside the cavity for the open cavity with $h = 5$ cm can be observed in the second attic from above in Fig. 4, where an air flow near to the roof running from inlet to outlet vents can be observed. This flow creates a convective barrier that carries important amounts of heat from the attic out to the external ambient, thus reducing the heat transferred to the ceiling. This socalled flow barrier is a buoyancy-driven convective flux created by the inlet air in contact with the roof, being the first cooler than the second.

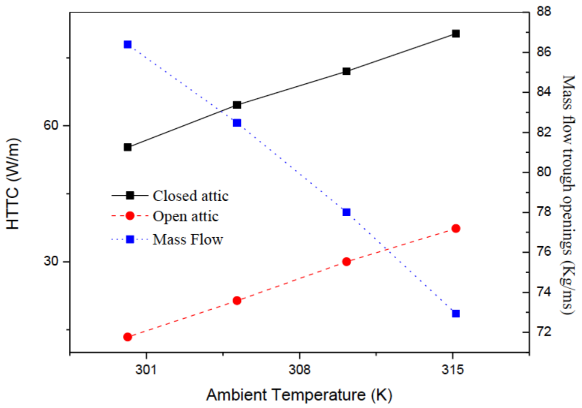

FIG. 3: Heat transferred through the ceiling for both closed and open cavity. Mass flow through the attic is plotted for the open cavity.

TABLE 2: Impact of ambient temperature.

Ambient Tempera-ture (K)	Closed Attic	Open Attic	
	Heat transfer to the ceiling (MW/m)		Mass flow (kg/ms)
300.15	55.3	13.4	86.4
305.15	64.6	21.4	82.5
310.15	72.0	30.0	78.0
315.15	80.3	37.3	72.9

Influence of vent (openings) size.

In the previous section, it was shown that the cavity with openings greatly improves the thermal performance of the attic. It is expected that the wider the openings, the higher the air flow rate through the attic, thus optimizing the convective heat exchange with the external environment. In this section, the attic thermal performance is explored for the following openings heights: 2 cm, 5 cm, 8 cm and 11 cm (see Fig. 4). The ambient air temperature was set to 305.15 K. The wider the openings, the greater the convective barrier near the ceiling and therefore the greater the heat dissipated convectively to the outside of the cavity, as can be seen in Fig. 4.

Fig. 5 shows that even for a small opening height of 2 cm, the HTTC is reduced up to 58 % respect to the closed cavity, while for the widest vents ($h = 11$ cm) the reduction exceeds 73 %, meaning that the wider the openings the better the attic thermal performance. This great reduction in HTTC is generated by the existence of a flow barrier close to the roof that gets thicker as openings size is increased (see Fig. 4), which transports convective heat to the outside of the attic, as was explained in the previous section. However, the HTTC reduction seems to be kept under 80 % for $h > 11$ cm, being this the maximum opening size we recommend.

Influence of roof pitch.

The roof pitch not only involves the possibility of thermal optimization, but also implies different material costs and water drainage performances. The minimum recommended pitch is 7º and this value should not exceed 20º. In this section, the thermal performance will be explored for a roof pitch ranging from 7º to 17.5º. For this purpose, the attic height at the center of the base (parameter *Am* in Fig. 1) will be kept constant at 0.8 m, to keep the attic volume constant.

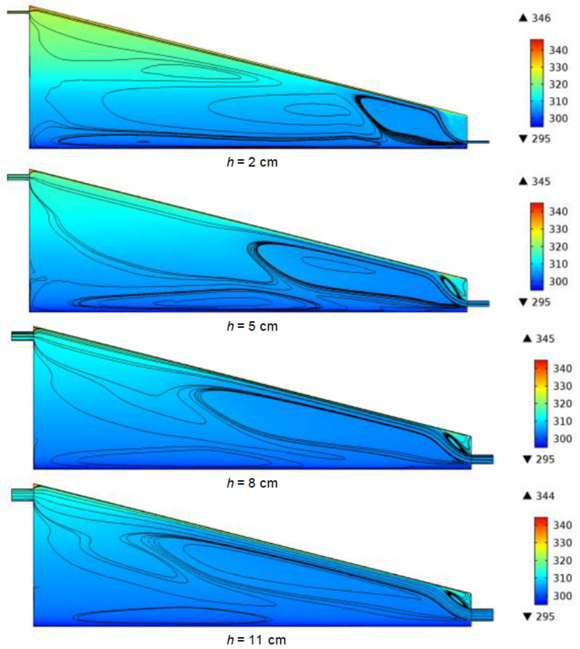

FIG. 4: Streamlines (black lines) and temperature field for an open cavity. Legends on the right show temperatures in K.

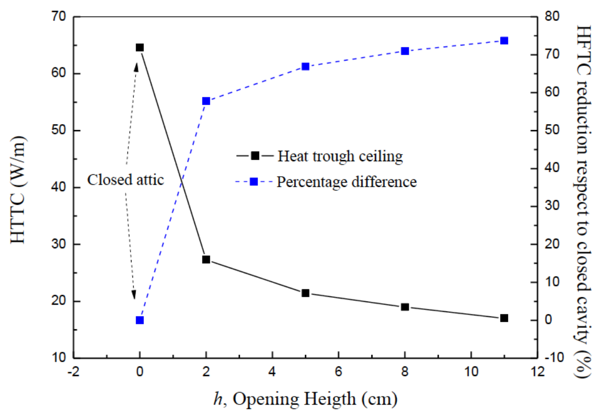

FIG. 5: Dashed curve: HTTC for every explored opening height. Solid curve: Percentage reduction of computed HTTC for the open attics with respect to that of the closed one.

The opening height was set to 5 cm.

Table 3 shows that the HTTC increases with roof inclination. One could expect that the higher the roof inclination the enhanced buoyancy effect and the greater the mass flow that carries convective heat out of the attic, but the reason for HTTC to be increased is that the higher the roof inclination the wider the roof area that is exposed to solar radiation. Although the mass flow increases, the proportion of heat transferred to the ceiling also increases. In this sense, a pitch of 7º seems to be the better choice from a thermal viewpoint, and it is the cheaper choice too. It can also be noted that for any roof inclination, the vented attic shows a very high reduction of the HTTC compared to a closed one, being this reduction about 63 % for a pitch of 7º and 67 % for 17.5º.

Influence of Attic volume.

Attic volume was also explored keeping both the roof pitch and the opening height constants, with values of $\theta =$

TABLE 3: Impact of roof pitch.

Roof Pitch (°)	Closed Attic	Open Attic	
	Heat transfer to the ceiling (MW/m)		Mass flow (kg/ms)
7	40.6	16.2	64.8
10.5	52.6	17.8	69.6
14	64.6	21.4	82.5
17.5	77.0	25.0	92.1

14° and $h = 5$ cm, respectively and varying the middle height of the attic (Am). The inclination was selected by considering the abundant rains in summer days of our zone. In this sense, roof drainage is critical.

Table 4 shows that the HTTC is reduced as Am increases, an expected trend because the taller the attic the greater the air volume that generates a natural insulation between the roof and the ceiling. For a vented attic, the HTTC reduction between the extreme volume sizes is 32 %, while this reduction is about 23 % for a closed one. Even though these reductions are important, the attic cannot be as tall as desired due to construction costs. Even for the lowest vented attic ($Am = 0.7$ m) the HTTC is 56 % lower than that for the tallest closed one ($Am = 1.0$ m). When comparing these results with the ones observed for different vent sizes, we can conclude that a vented attic needs an optimization of its openings instead of the roof height to greatly reduce the HTTC without requiring higher construction costs. Due to the lack of ventilation, the attic volume is more important to be higher for a closed cavity.

TABLE 4: Impact of attic middle height.

Attic Middle Height (m)	Heat transfer to the ceiling (MW/m)	
	Closed Attic	Open Attic
0.7	73.6	23.9
0.8	64.6	21.5
0.9	59.3	19.2
1.0	55.2	17.0

IV. CONCLUSIONS

A low Reynolds number $k-\varepsilon$ turbulent model was numerically solved to analyze the natural ventilation influence on an open cavity which resembles the attic of a low-cost family house. The model was validated with experimental and numerical models, showing good agreements in both cases. The analysis was focused on studying how simple construction parameters can reduce the heat transferred to the interior of the house, i.e., openings sizes, roof pitch and attic volume. By exploring these parameters, we found that:

- The wider the openings (inlet and outlet), the better the attic thermal performance.
- The lower the roof pitch, the lower the HTTC due to a lower surface exposed to solar radiation.
- For a closed attic, the greater its inner volume the better the thermal performance. For a vented attic, the volume is not as important as the openings size to have an important reduction of the HTTC.

Opening's existence is the most important feature that can enhance the attic thermal performance. It was shown that a vented attic can reduce the HTTC in more than 70 % with respect to a closed one for summer conditions of Santa Fe (Argentina). As limitations, we can mention that winds, winter conditions, ceiling insulations and possible 3D effects of different internal attic geometries were not considered in this work.

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