A simplified model to estimate Natural Ventilation flows crossing simple dwelling layouts

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Abstract
The paper presents a procedure to estimate Natural Ventilation flow rates trough buildings assuming general flow patterns can be accessed. The principle is to assume the flow path known and the whole building as an association of ducts that could be considered either as series or as branches and then establish an equivalent characteristic curve. The main driving force is the pressure difference on facades, expressed *via* the respective pressure coefficients, together with an appropriate reference wind velocity. A thermal component may be added establishing the final value. A set of curves related with the variables involved is drawn in order to build a four-quadrant graphic allowing for an easy application of the procedure.

Keywords: Natural Ventilation, air flow, system characteristic, wind driven ventilation

1. INTRODUCTION

When a zone to be naturally ventilated shows an identifiable flow path between inlets and outlets it's likely to describe it as a ducted flow and so to define a characteristic curve. Possible flow paths being defined an equivalent duct system can be built out of a mix of series or parallel arrangements and an equivalent head loss coefficient estimated for the complete system. The head losses along the flow path correspond to wall shear and to singularities.

As for forced ventilation systems the losses must be balanced by the head.

The driving head is provided by the difference between external pressures in the facades resulting from the wind action over the building together with a thermal action provided by air density differences due to internal heat sources or sinks.

With a characteristic curve established for the system and a driving head equivalent to a mechanical ventilator assessed it is possible to express the energy balance in a graphical form assembling the curves representing the different contributions in an abacus for Natural Ventilation flow estimates. The graphic procedure has the advantage of solving the non linear equation system generally built for this type of problems in an easy way.

2. BASICS

2.1 The system characteristic

The flow established through the building between external openings is similar to a closed circuit because atmospheric pressure is present at both ends and so to build the characteristic only pressure losses (namely the loss of kinetic energy to the exterior) have to be accounted for. The general form of the system's characteristic, is

$$\Delta P_h = \frac{1}{2}\rho k U^2 = KQ^2 \qquad (1)$$

ΔP_h being the pressure loss, ρ the fluid density, k and K are the loss coefficients, representing the system resistance, expressed either in terms of the flow velocity, U, or of the volumetric flow, Q, and g the gravity acceleration.

Flow pressure losses depend on two well known mechanisms:

i) Friction effects, ΔPh_f, between the fluid and the wall expressed by,

$$\Delta P_{hf} = \frac{1}{2} \rho \, (4f \frac{L}{D}) \, U_{in}^2 \qquad (2)$$

f being the friction factor, L the length, D the equivalent hydraulic diameter, and U_{in} the local velocity; and

ii) singularities along the flow path, the individual head losses, ΔP_{hs}, being,

$$\Delta P_{hs} = \frac{1}{2} \rho \, \zeta \, U_s^2 \qquad (3)$$

where ζ is each singularity own loss coefficient (considered as constant for a wide range of Reynolds number) and U_s the flow velocity through the singularity.

Notice that pressure losses may also be expressed in terms of heights (head) thus meaning energy losses per unit of specific gravity.

2.2 The system driving pressures

The system driving pressures arrives from two mechanisms:

i) one, mechanical associated with the external pressure distribution over the building facades where local pressures, P^E, can be expressed by

$$P^E = \frac{1}{2} \rho Cp \, U_0^2 \qquad (4)$$

U_0 being the wind velocity - typical values can be accessed in probabilistic terms from local meteorological stations - and Cp the local pressure coefficient - values can be found on bibliography [RSA (1983), Liddament (1996) or Orme *at all* (1998), for example] or, for more specific cases, obtained trough wind tunnel tests over models of the building and its surroundings. The mechanical contribution to driving pressures, the external pressure difference, ΔP^w, is then

$$\Delta P^W = \frac{1}{2} \rho \, \Delta Cp \, U_0^2 \qquad (5)$$

where ΔCp is the difference of pressure coefficients at the openings (see Figures 1 and 4); and

ii) the other, thermal, the so called stack effect - associated with the density difference between inside and outside air due to the presence of internal heat sources or sinks - being accessed as a buoyancy, since pressure differences, ΔP^T, are hydrostatic and may be written as

$$\Delta P^T = \rho g \frac{\Delta T}{\overline{T}} h \qquad 6)$$

h being the height difference between inlet and outlet; (Figure 2). Boussinesq approach is considered - $\Delta\rho/\rho = \Delta T/T$ - and air is assumed as a perfect gas so that density difference is expressed in terms of relative temperature difference, the over bar in equation meaning an average value.

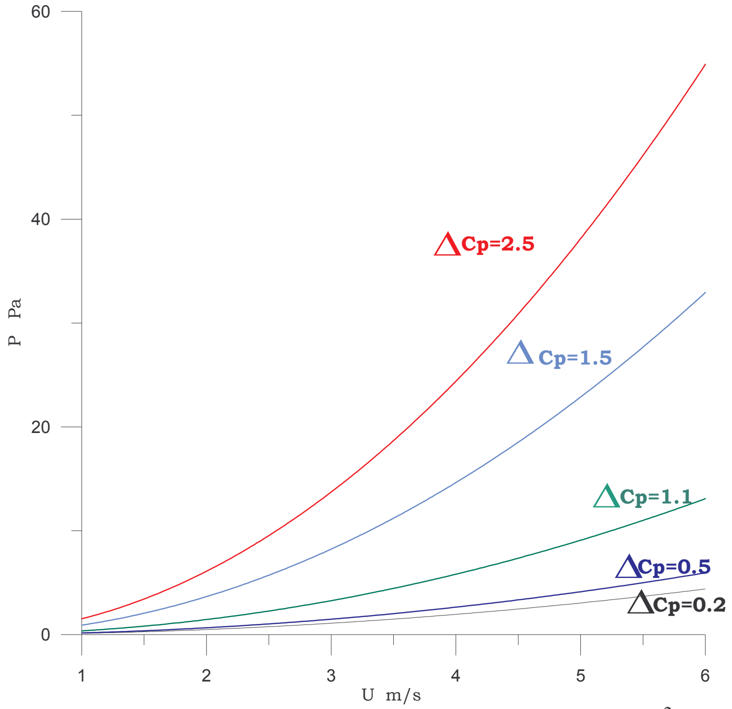

Figure 1 – Equation [5] (assuming ρ=1.22 kg/m^3)

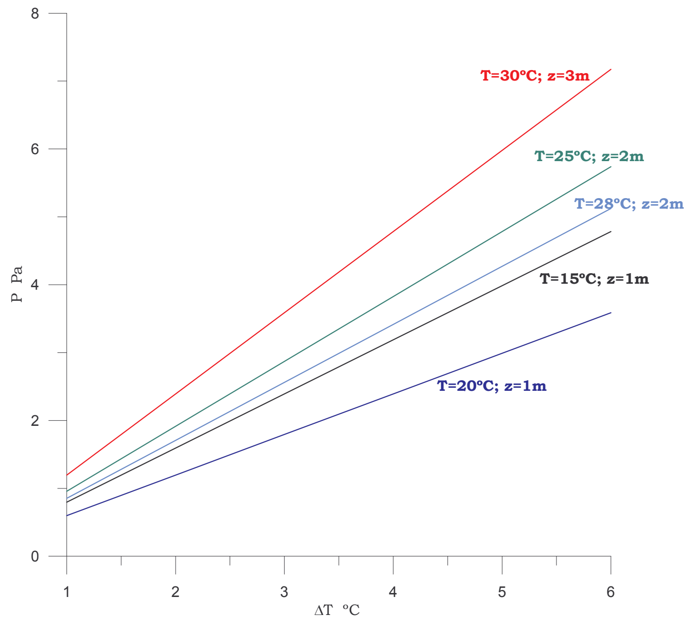

Figure 2 – Equation (6)

The total driving pressure is the arithmetic sum of both terms but attention must be paid to the fact that there is an interaction between the mechanisms as the temperature difference is computed by the energy balance equation (see Figure 3)

$$\Delta T = \frac{W}{\rho \, Q \, c_p} \qquad (7)$$

where W is the power of the internal heat sources and sinks and c_p is the specific heat of air. An iterative procedure has to be established

Usually, at least on moderate and warm climates, the mechanical source raises more important flows than the thermal one.

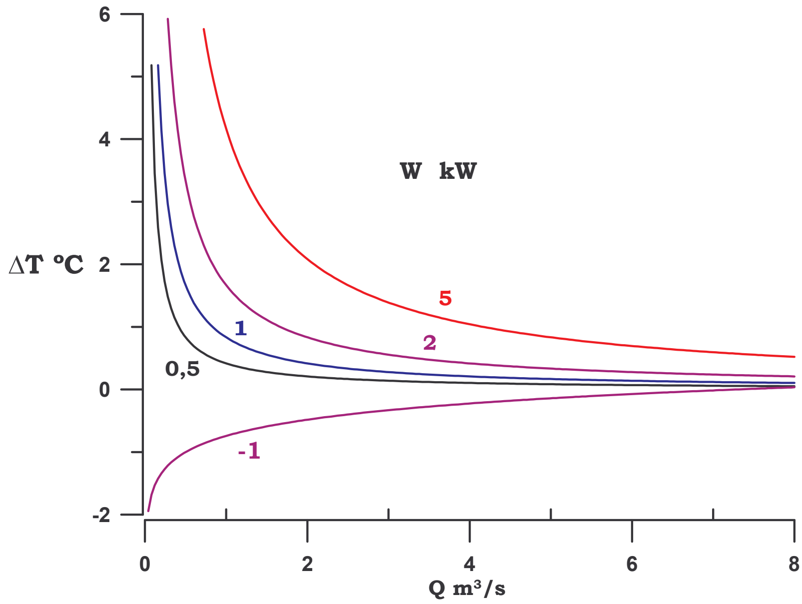

Figure 3 – Equation (7)

2.3 The system balance

The system will demand that pressure P

$$P = P^E + P^T \tag{8}$$

balance the loss ΔP_h, defined in equation (1). So

$$P = \Delta P_h = KQ^2 \tag{9}$$

represents the system equation under stationary conditions.

3. INTERNAL AIR FLOWS

The assumption that air entering a given space spreads, leading to flow velocities well below the ones through the openings connecting spaces and that room lengths are small compared with their hydraulic diameter, makes acceptable to consider the losses concentrated on the singularities. Furthermore the lay-out of spaces to be naturally ventilated may be viewed as series or branches (parallel), similar to a duct system.

For a series the equivalent pressure loss comes from adding up all individual losses weighted by their respective flow velocity [Gerhart and Gross (1985)],

$$\Delta P_h{}^S = \frac{1}{2}\rho\left[\left(\sum \varsigma_i\right)U_i^2 + \left(\sum \varsigma_j\right)U_j^2\right] \tag{10}$$

For incompressible and isothermal flow mass conservation reduces to flow conservation, that is UA=Q=Const., allowing to rewrite equation (10) as,

$$\Delta P_h{}^S = \frac{1}{2}\rho\left(\frac{\sum \varsigma_i}{A_i^2} + \frac{\sum \varsigma_j}{A_j^2}\right)Q^2 = KQ^2 \tag{11}$$

A being the area of reference in the series element (namely that of the opening) and K is the system resistance coefficient, in equation (1).

Assuming that wind driven flows are the main source of ventilation and taking equations (5), (9), and (11) it's possible to establish an expression to evaluate the ventilation flow,

$$Q = U_0 \sqrt{\frac{\rho\ \Delta Cp}{2\ K}} \qquad (12)$$

where,

$$K = \frac{1}{2}\rho\left(\frac{\sum \varsigma_i}{A_i^2} + \frac{\sum \varsigma_j}{A_j^2}\right) \qquad 13)$$

In a parallel arrangement the pressure loss is the same for all the branches ($\Delta P_{h1} = \Delta P_{hi} = \Delta P_{hn} = \Delta P_h$) [Gerhart and Gross (1985)] so the characteristic curves are,

$$\Delta P_h = K_i Q_i^2 = K^P \left(\sum_i Q_i\right)^2 \qquad (14)$$

or

$$\Delta P_h = K^P \left(\sum_i Q_i^2 + 2\sum_{i \neq j} Q_i Q_j\right) \qquad (15)$$

Replacing Q^2 by $\Delta P_h/K$ and Q_iQ_j by $\Delta P_h / \sqrt{K_i K_j}$ the parallel equivalent resistance coefficient arises ($i \neq j$),

$$\frac{1}{K^P} = \sum \frac{1}{K_i} + 2\sum \frac{1}{\sqrt{K_i K_j}} \qquad (16)$$

It is easy, from the equilibrium of pressure losses in the different branches, to establish the flow in each branch,

$$K_i Q_i^2 = K_i(\alpha_i.Q)^2 = K^P Q^2 \qquad (17)$$

and then

$$\alpha_i = \sqrt{K^P / K_i} \qquad (18)$$

where α_i is the fraction of the whole flow through the i branch.

For a system with only two branches, equation (19) will be

$$K_1(\alpha_1 Q)^2 = K_2[(1-\alpha_1)Q]^2 \quad (19)$$

a second degree equation where only the positive root below unit has a physical meaning, equation (20)

$$\alpha_1 = \frac{-K_1 \pm \sqrt{K_1 K_2}}{K_1 - K_2} \qquad (20)$$

With an equivalent series element for each parallel flow it is possible to apply equation (13) to obtain the value for the system resistance, K, and then to introduce it in the system equation (9)

4. EXAMPLE

Let us consider the multi-zone space (typical of what is called a T2 apartment in Portugal) on Figure 4.

The zones to be considered are E1-E2-E3 (the other ones - a WC and a guest or service room - being closed) where openings *ab1* to *ab5* are present and their characteristic values are resumed in Table 1.

Openings *ab1-ab3* are in a series arrangement; their resultant being a branch of a parallel with *ab2* and, from here, its equivalent is in a series with *ab4-ab5*.

Table 1 – Opening characteristics

Opening	Cp	A[m^2]	ζ
Ab1	0.7	1.28	2.5
Ab2	0.7	1.28	2.5
Ab3	-----	1.89	2.5
Ab4	-----	1.89	2.5
Ab5	-0.4	1.28	2.5

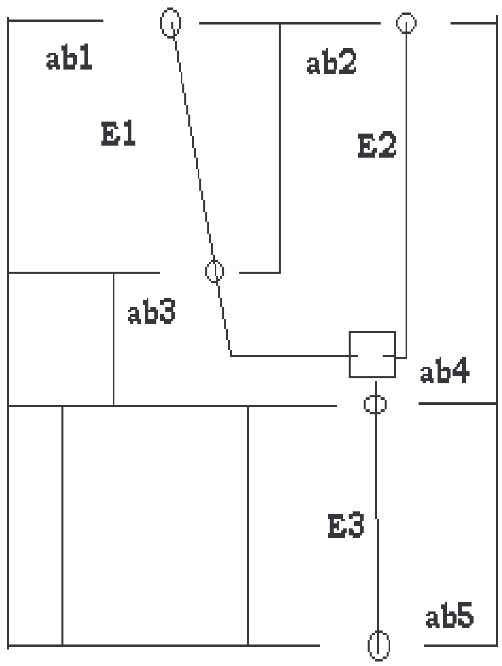

Figure 4 – Dwelling layout

The mathematical transcription being,

$$K_S^{E1} = \frac{1}{2}\rho\left(\frac{2.5}{1.28^2} + \frac{2.5}{1.89^2}\right) = 1.36$$

$$K^{ab2} = \frac{1}{2}\rho\frac{2.5}{1.28^2} = 0.93$$

$$\frac{1}{K_P^{E2}} = \frac{1}{1.36} + \frac{1}{0.93} + \frac{2}{\sqrt{1.36 * 0.93}} = 3.6 \Rightarrow K_P^{E2} = 0.28$$

$$K_S^{E3} = \frac{1}{2}\rho\left(\frac{0.28}{1.89^2} + \frac{2.5}{1.28^2} + \frac{2.5}{1.89^2}\right) = 1.4$$

and, according to eq. (11), the system characteristic will write,

$$P = 1.4\, Q^2 \qquad (21)$$

Assuming a wind velocity of U_0=4m/s, the wind driven head (eq. (5)) is,

$$\Delta P^E = \frac{1}{2} * 1.22 * 4^2 = 10.7 \quad \text{Pa}$$

the ventilation flow will being (eq.(9) or eq. (12)),

$$Q = 4\sqrt{\frac{1.22 * 1.1}{2 * 1.4}} = \sqrt{\frac{10.7}{1.4}}$$

Q=2.8 m^3/s.

Eq. (20) allow to establish that the flow through E1 is 1.3 m^3/s and through E2 of 1.5 m^3/s, the coefficient α being,

$$\alpha = \frac{-0.93 \pm \sqrt{1.36 * 0.93}}{1.36 - 0.93} = 0.45$$

The global ventilation flow may be obtained by graphical means (see figure5).

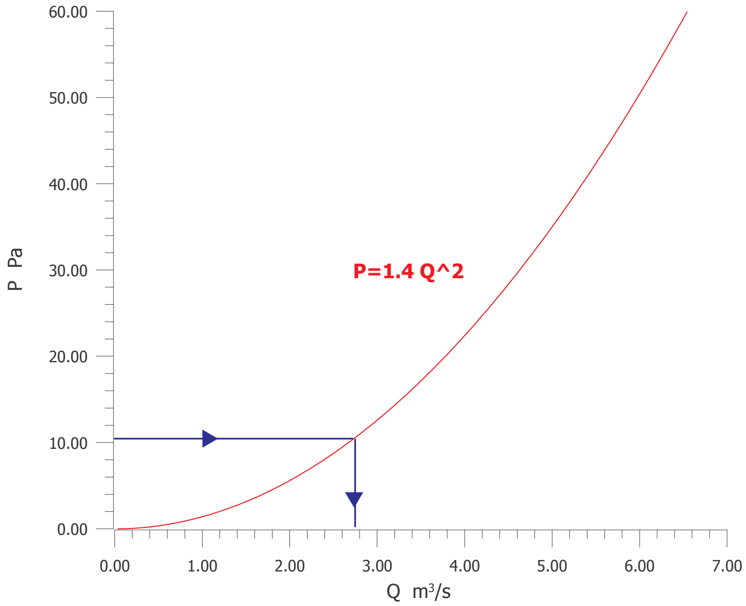

Figure 5 – Equations (1) and (21)

5. ABACUS

It's now possible to assemble under graphical form the whole procedure of estimate natural ventilation flows on simple layouts. Figure 6 represents an abacus for that purpose.

Starting by the wind velocity ① and the ΔCp curves ② (see figures 1 and 6) one gets the head associated with the mechanical energy source③, H^w, is estimated. Together with the system characteristic, eq. (9), ④ (see Figures 5 and 6), is possible to obtain a first estimate of the wind driven internal flow ⑤.

Then with the heat source being known (a 2 kW heat source in the example) ⑥ the temperature increase is evaluated (eq. (6) fig. 3 and 6) ⑦ and the Boussinesq approach can be applied (abacus of Fig. 6, third quadrant, and Fig. 2).
Now together with the internal temperature and the height difference between openings ⑧ an evaluation of the thermal energy source ⑨, (eq. (6) and Figures 2 and 6), can be performed and added up to he mechanical source ⑩.
A new flow is then estimated (Figs. 5 and 6) and a new loop is started.
The process converges.

Notice that the inclusion of a fan is possible adding its own flow output to the one obtained on the natural ventilation process⑤, on the Q axis.

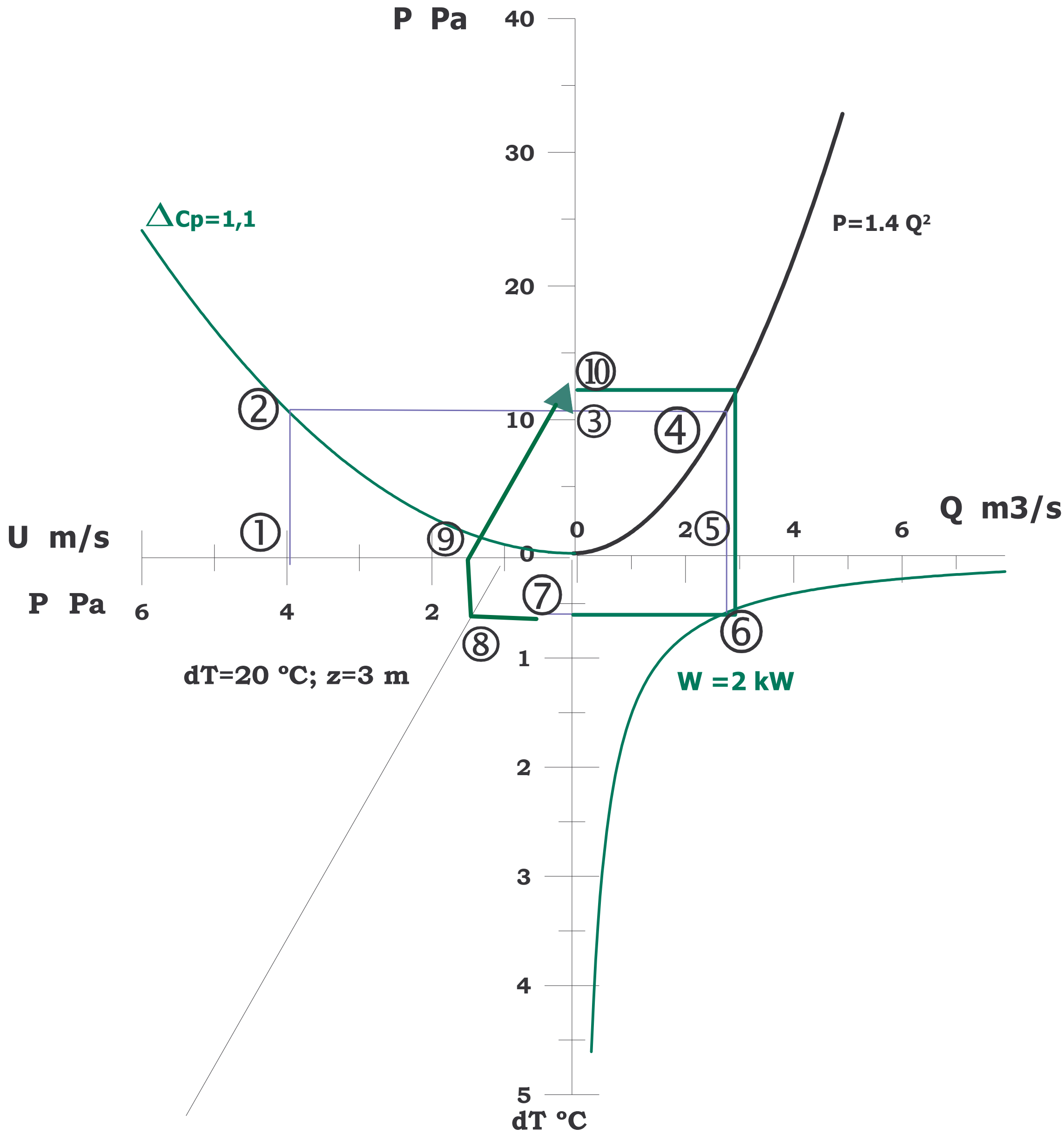

Figure 6- Abacus to estimate natural ventilation flows on simple layouts

6. VALIDATION

An estimate of a NV process for a building with a number of internal zones is characterised by the knowledge of the flow velocity through any opening and the pressure, temperature and density variation for each one of the zones.

VENTIL is a multi-zone model [Saraiva *et al.* (1985); Marques da Silva *et al.* (1998 - 2003)] that assembles a set of non linear equations achieving that target:

- A mass balance equation for each zone (eq. (22)) and the overall building (eq. (23)). In addition flow velocities for any opening of connecting zones must cancel (eq. (24));
- A momentum balance equation (Bernoulli eq.) for each interior (eq. (25)) and external (eq. (26)) opening;

- An energy balance equation for each zone (eq. (27)), and the overall building (eq. (28));
- The perfect gas law.

$$\sum_{K} U_{ab} A_{ab} = 0 \tag{22}$$

$$\sum_{I} \sum_{K} U_{ab} A_{ab} = 0 \tag{23}$$

$$U_{ab}{}^{I} + U_{ab}{}^{I'} = 0 \tag{24}$$

$$\left(\Delta\rho^{I} H_{ab}{}^{I} - \Delta\rho^{I'} H_{ab}{}^{I'}\right) g + \left(\Delta P^{I} - \Delta P^{I'}\right) - \frac{1}{2} \zeta \rho_0 U_{ab} \left|U_{ab}\right| = 0 \tag{25}$$

$$\Delta\rho^{I} H_{ab}{}^{I} g + \left(\frac{1}{2} Cp_{ab}\ \rho_0 U_0{}^{2} - \Delta P^{I}\right) - \frac{1}{2} \zeta \rho_0 U_{ab} \left|U_{ab}\right| = 0 \tag{26}$$

$$Q^{I} + \sum_{K} \rho_0\, Cp_{ar}\, U_{ab} A_{ab} \Delta T^{I} + \sum_{w} h_w A_w \left(\Delta T^{I} - \Delta T^{I'}\right) = 0 \tag{27}$$

VENTIL estimates a flow of 2.6 m^3/s for the referred layout and conditions, and that 45% of it flows through E1 zone.

7. CONCLUSIONS

The main conclusion is that a general graphical procedure to estimate natural ventilation air flows, gathering in a single abacus both the mechanical (wind) and thermal (stack) components can be built, figure 7, as a direct generalization of Fig. 6. The advantage of using it lies in the fact that the trouble arising from the need to solve the non linear equation system that describes the problem is avoided.

The first quadrant will be used to draw the specific system characteristic as from eqs, (11) to (16).

The process is based on the concept of similitude of the flow path with a duct system when line loss can be discarded. The driven forces between duct ends (wind and stack effects are added) being needed as well as the system characteristic (head loss).

A limitation to the described procedure lays on the fact that it applies to layouts where the flow path (qualitatively not quantitatively) must be previously known.

A second abacus can be built for cooling thermal loads where the curves on the second quadrant should be reversed (see fig. 3) and temperatures decrease.

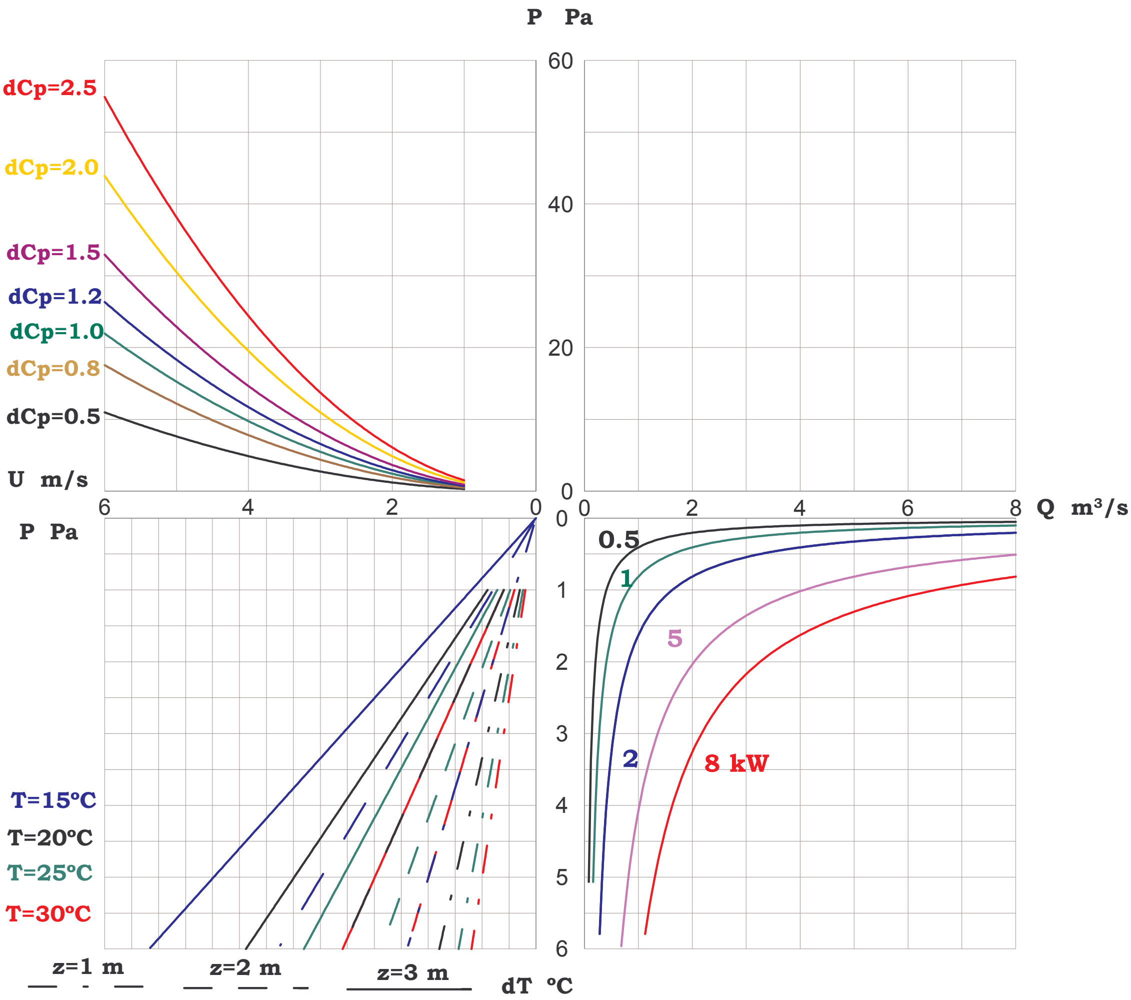

Figure 7- Abacus to estimate natural ventilation flows on simple layouts

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