VENTILATION MODELS

This thesis work is aiming to build a *building ventilation model*, on a set of resistances and generators, which would include natural air movement as well as fan powered air flows. The model could yield infiltration and exfiltration flows referring to fan pressurization test method [27], [28], [29]. The ventilation model complexity should be adapted to the building under study (residential, commercial) and should be able to provide a good estimation of the indoor air quality level, of the thermal comfort when free-cooling is performed, and of the building energy balance.

The use of a solver such as EES is then very convenient for that purpose because it allows equations not to be written in an explicit form.

A generic ventilation model can be first described (§ 6.1). It can be applied to yield natural ventilation air flow rates in a house and in an office building (§ 6.2 and 6.3).

Fan powered air flows can be added either by imposing a given air flow rate (§ 6.2.3) or by introducing a fan model connected to an air duct network model (§ 6.3.2).

6.1. Ventilation model description

The *building ventilation model* can be based on a set of resistances and generators. By analogy with electricity, pressure and air flow rate can respectively correspond to electric potential and strength of the current (fig. 6.1).

A resistance means a *pressure drop* which can be expressed as function of the *mass air flow rate* in a way that allows both quantities to be positive or negative, depending on the air flow direction:

$$\Delta p = K.\left|\dot{M}\right|^{n}.\dot{M} \qquad (6.1)$$

Δp: Pressure drop through ventilation aperture *Pa*
$\dot{M}$: Mass air flow rate through ventilation aperture *kg/s*
n: Exponent ranging from *0* when the flow is laminar to *1* for a turbulent flow
K: Constant $Pa.(s/kg)^{1+n}$

An *n* exponent and a *K* constant can be adopted:

- For infiltration and exfiltration air flow rates. An average leakage area of $5\ cm^2$ per m^2 of external walls can be observed on 15 Belgian houses in 1982 [51]. The corresponding air flow rate, expressed for a 50 Pa indoor-outdoor pressure difference, equals 16 m^3/h per m^2 of wall area. A *K* constant can be deduced from that average value.

- For natural ventilation devices: Controlled supply orifices (CSO), transfer orifices (TO) as well as controlled exhaust orifices (CEO).

- For air ducts, as function of the Reynolds number and of the roughness.

The *pressure generators* can be provided by wind (6.2) and buoyancy (6.3).

Wind pressure acts perpendicularly to the external air orifice as function or the square of wind speed:

$$\Delta p_{wind} = p_c . \frac{u_{wind}^2}{2.v_{out}} \tag{6.2}$$

p_c: Wind pressure factor -
u_{wind}: Wind speed *m/s*
v_{out}: Outdoor air specific volume *m³/kg*

Buoyancy results from the difference of air specific volumes as function of the level:

$$\Delta p_{buoyancy} = g . \frac{(z_2 - z_1)}{v} \tag{6.3}$$

g: Acceleration of gravity *m/s²*
v: Air specific volume *m³/kg*
$z_1 z_2$: Levels *m*

Fans can be dealt with either by *imposing air flow rates* on some model indoor nodes (fig. 6.3) or by introducing *pressure generators*. A specific fan model can then be connected to an air duct network (annexes 5 and 6).

The air flow rates are computed through *mass air flow rate balance* at each model *node* and through *pressure equilibrium* for each model *loop*.

For example, the model of fig. 6.1 yields the mass air flow rate balance of zone 1 node:

$$\dot{M}_{cso,pr,1} + \dot{M}_{cso,dp,1} + \dot{M}_{CEO,1} = \dot{M}_{z1z2}$$

And the pressure equilibrium corresponding to the left loop can be written:

$$-\Delta p_{wind,pr,1} + \Delta p_{cso,pr,1} + \Delta p_{TO} + \Delta p_{buo,in} - \Delta p_{cso,pr,2} + \Delta p_{wind,pr,2} - \Delta p_{buo,out} = 0$$

6.2. Ventilation model adapted to houses

A house ventilation model can be associated with the two zones lumped model (chapter 5, fig. 5.33), in order to yield a complete house model able to estimate the indoor air quality level, the summer thermal comfort when windows are opened, and the house energy balance.

The generic model (§6.1) can be adapted first to build a house *natural ventilation model* including controlled air supply grids. Then a model of *window stack effect* can be added to handle for opened windows air flow rates. Finally, *fan* powered supply or exhaust air flow rates can complete the house ventilation model.

6.2.1 Natural ventilation model

Belgian standards define a house *type A* natural ventilation as including the following devices: dry rooms are provided with Controlled Supply grids, doors interconnecting dry rooms and humid rooms are provided with Transfer Orifices grids, and humid rooms are provided with Controlled Exhaust vertical ducts.

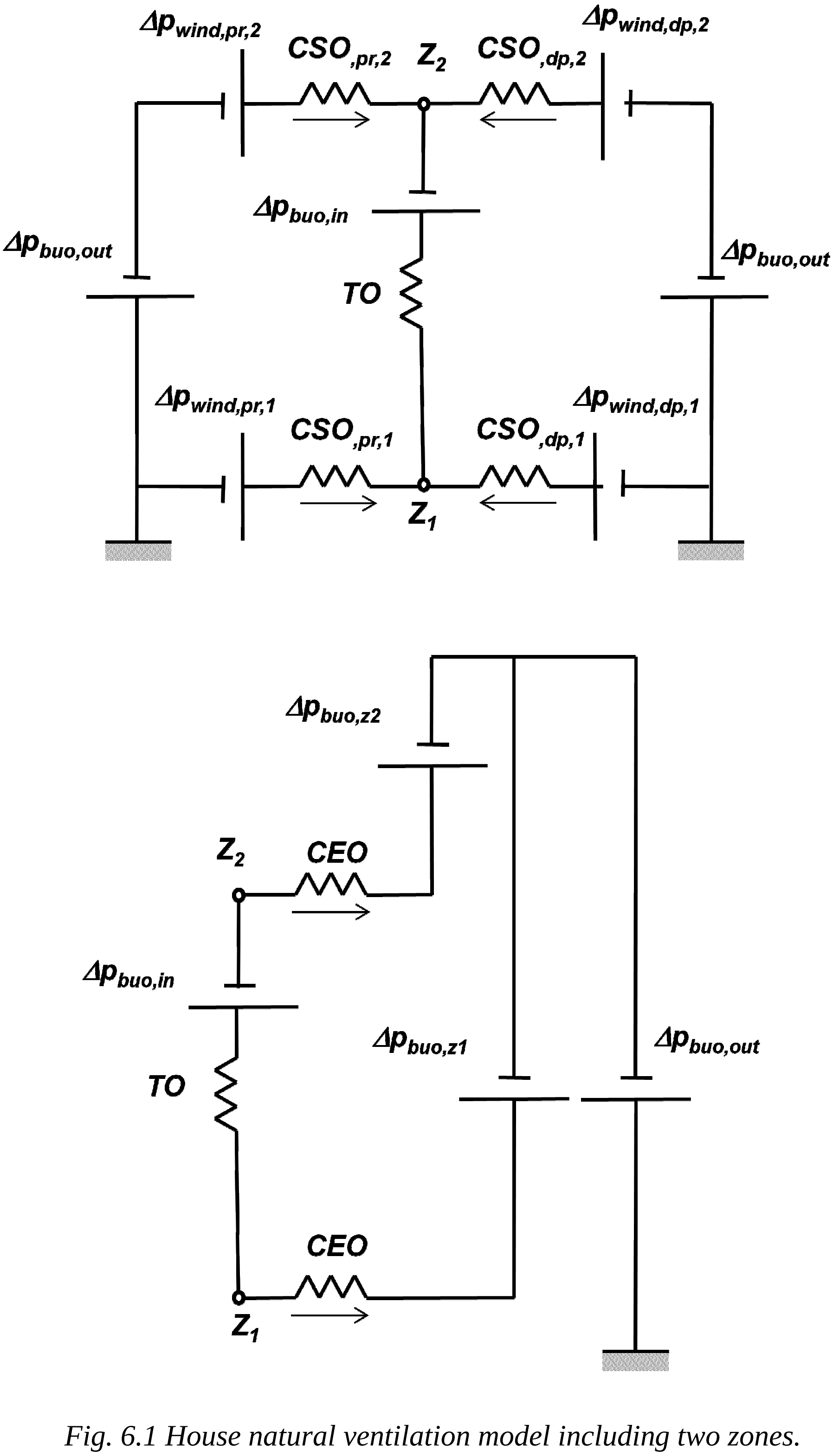


Fig. 6.1 House natural ventilation model including two zones.

Starting from the principles exposed in §6.1, a model can be built for a two storey house (fig. 6.1). It can handle air flow rates crossing Controlled Supply Orifices. Those can be shared in two categories: pressurized and depressurized orifices. As wind turns, an average pressure factor can be computed for each orifices category.

The dry rooms in a zone are interconnected and represented by a single node. A global Controlled Exhaust Orifice *K* coefficient can handle the pressure drops from the zone to the outdoor, through the following serial devices: a Transfer Orifice grid interconnecting the zone dry rooms and humid rooms, an exhaust grid and an exhaust vertical duct (fig. 6.1 down). The exhaust vertical air duct is sized from a given nominal exhaust air flow rate, for an air speed equal to 1 *m/s*.

The model can account for Transfer Orifices interconnecting both zones (fig. 6.1 up). A staircase stack effect can link them. This is performed through a Transfer Orifice, whose *K* coefficient characterizes the pressure drop occurring through the parallel apertures located beneath the doors interconnecting zone 1 and the staircase. So, zone 1 rooms are supposed to be interconnected through opened doors (from living to kitchen), while zone 2 rooms are supposed to be all connected to the staircase through opened doors.

The house ventilation model equations are listed in annex 6 §6.1.1. They aren't explicit so that a solver such as EES is very convenient to handle them. The model *inputs* are the pressures provided by the generators, the model *parameters* are the apertures *K* coefficients and *n* exponents (6.1), and the model *outputs* are the air flow rates.

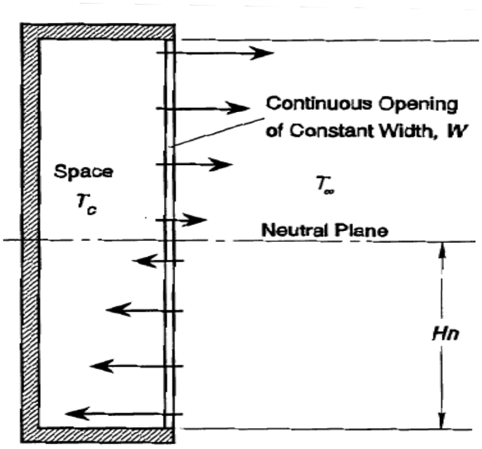
6.2.2. Window stack effect

The ventilation model displayed on fig. 6.1 can handle airflows crossing the house but it can't evaluate the air renewal rate provided by an opened window to a closed room, independently from cross ventilation effects. A *window stack effect* can be added to complete the ventilation model.

The window stack effect (fig 6.2, left) is the height varying, hydrostatic, indoor-outdoor pressure difference caused by the difference in specific volume of the two bodies of air, which, in turn, is caused by the difference in temperature of the two bodies of air (ref. [28],[30],[38]).

Windows air flow rates can be handled partially in parallel with controlled supply orifices, and partially at a lower level equal to half the window height, in order to reproduce the window stack effect (fig 6.2, right). The model equations are listed in annex 6 §6.1.2.

This window model is added to each zone ventilation branch of both models (house and office) (fig. 6.1 and 6.5).



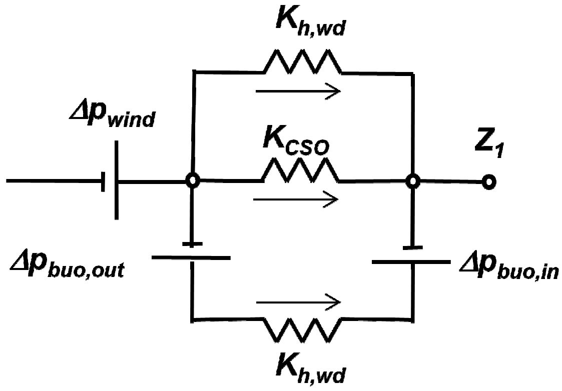


Fig. 6.2 Window stack effect (left) [38] and model of window stack effect coupled with Controlled Supply Orifices (right).

6.2.3 Combined natural and fan powered ventilation

A combined ventilation model includes *natural entities* such as leakage, Controlled Supply Orifices, Transfer Orifices, Controlled Exhaust Orifices, and *mechanical entities* such as air supply fans and air exhaust fans with their associated air duct systems, all entities interacting with each other.

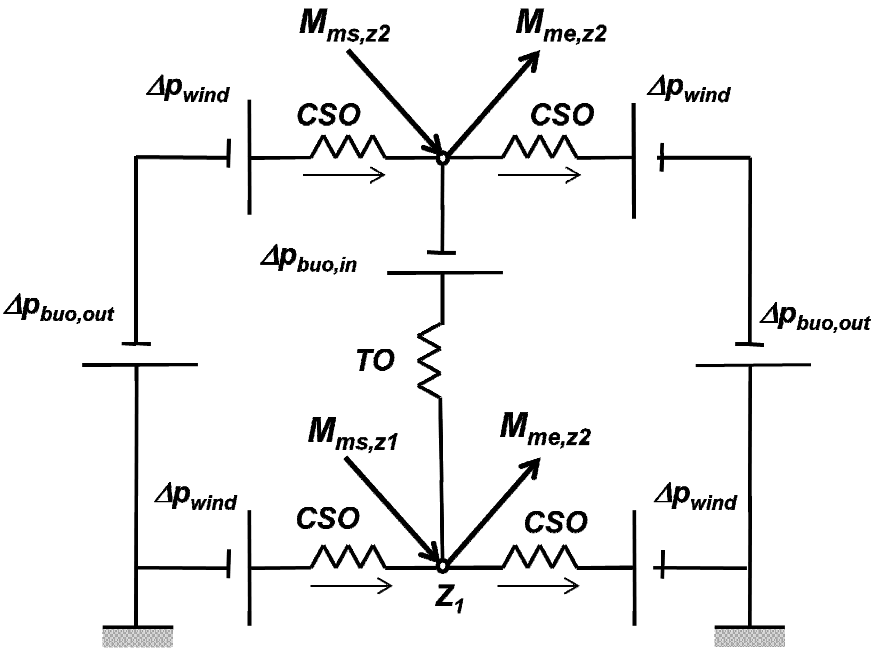


Fig. 6.3 Model of combined natural/fan powered ventilation adapted to a house. The model must be completed with the exhaust duct branch represented on fig. 6.1 down.

A first simple way to deal with combined ventilation is to impose the fans supply and exhaust air flow rates by just adding them, when they exist, to the node air flow rate balances (fig. 6.3). That model, based on *imposed fan air flow rates* can be used in residential buildings.

As such, the model can handle four ventilation systems:

- A: natural air supply through Controlled Supply Orifices, air transfer through Transfer Orifices and natural air exhaust through Controlled Exhaust Orifices (§ 6.2.1, fig 6.1).
- B: fan powered air supply, air transfer through Transfer Orifices and natural air exhaust through Controlled Exhaust Orifices.
- C: natural air supply through Controlled Supply Orifices, natural air transfer through Transfer Orifices and fan powered air exhaust.
- D: fan powered air supply, air transfer through Transfer Orifices and fan powered air exhaust, with possible air heat recovery.

The model equations are listed in annex 6 §6.1.3. This model doesn't account for the complete interaction between the fan and the building pressure/air flow rate laws as the equations establishing the location of the fan running point are skipped.

6.3. Ventilation model adapted to office buildings

The thesis is aiming to build a ventilation model which would be able to estimate the offices indoor air quality level, the thermal comfort when natural free-cooling is performed, and the energy balance.

The office building ventilation model can be associated with the five zones lumped model presented in chapter 5, fig. 5.34, in order to provide a complete model of an office building area.

6.3.1. Natural ventilation model description

A first model was built to analyse offices indoor air quality for three natural ventilation strategies:

1. Offices can only be provided with Controlled Supply Orifices in the facade and Transfer Orifices to the corridor (fig. 6.4 up left).

2. Offices can be provided with Controlled Supply Orifices in the facade and Transfer Orifices to the corridor. Moreover, windows can be opened until 10% of their area each day for an hour during the midday time, when outdoor temperature is higher than 5°C (fig. 6.4 up right).

3. Offices can be provided with Controlled Supply Orifices and Transfer Orifices, and can be connected to a stack effect from a staircase, elevator shaft or ventilation shaft (fig. 6.4 down).

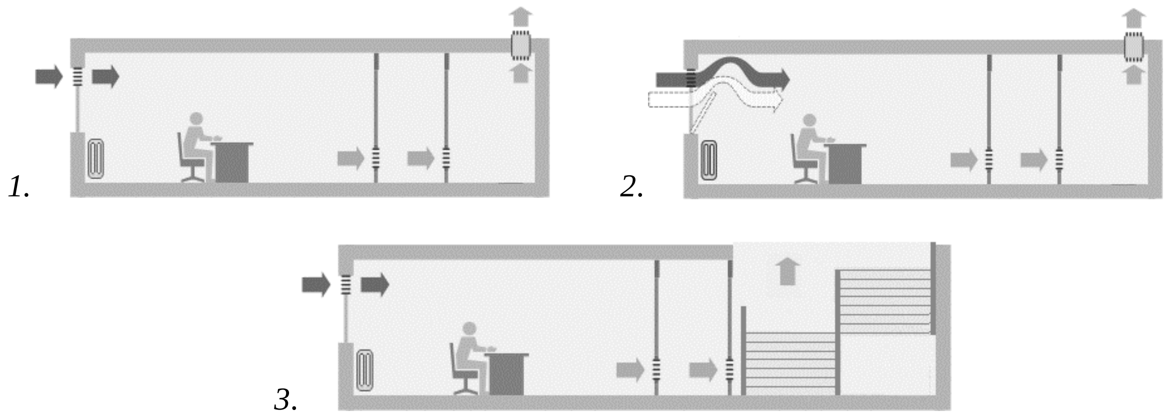


Fig 6.4: Natural ventilation strategies for offices [39].

From the generic equations (§6.1), a five zones model can be built to deal with those different ventilation strategies, office rooms being considered as separate zones connected to the corridor through transfer orifices (fig. 6.5). A window model can be added to each branch connecting a zone with the outdoor (fig. 6.2).

Controlled Supply Orifices can be sized to reach 2.9 m³/h.m² of office floor area for a pressure difference of 2 Pa. Transfer Orifices from office to corridor can be sized for the same air flow rates as office Controlled Supply Orifices (ref. [37]). The corridor can be connected to a ventilation shaft through a Controlled Exhaust Orifice.

The model equations are listed in annex 6 §6.2.1.

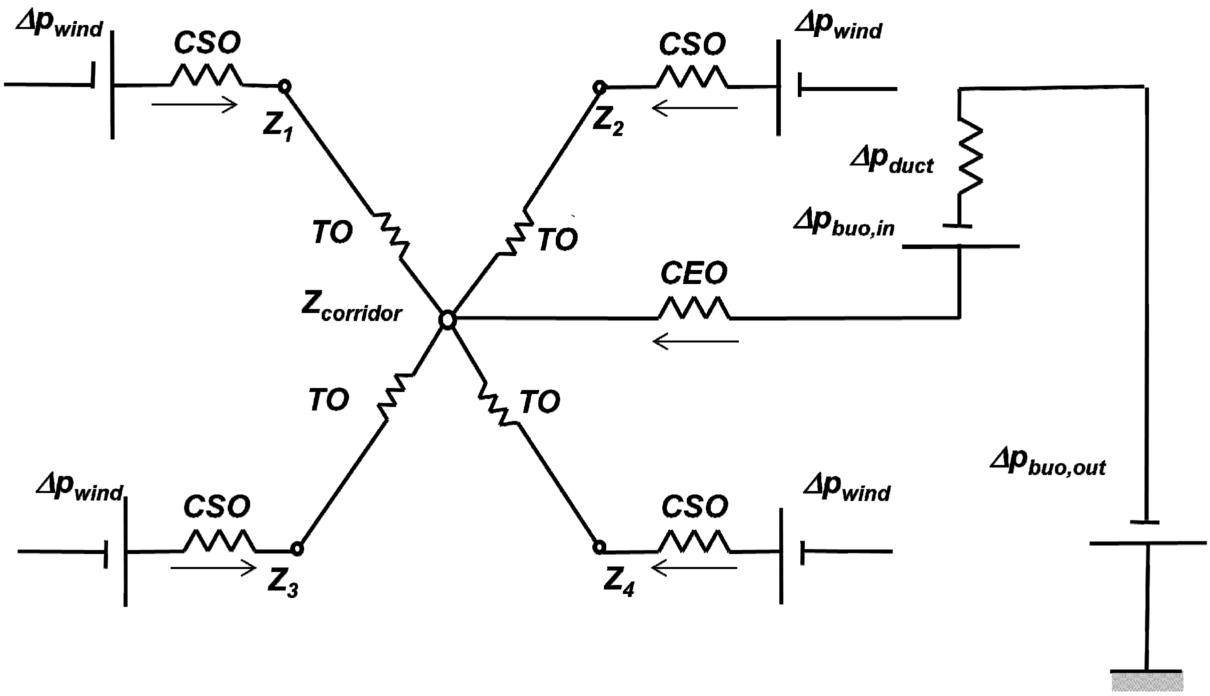


Fig. 6.5 Natural ventilation model adapted to an office building area.

6.3.2. Combined natural and fan powered ventilation

A combined ventilation model includes natural as well as fan powered ventilation entities. Modelling combined ventilation systems can be necessary in office buildings, particularly to simulate variable air flow rate systems.

Combination of natural/mechanical ventilation can be dealt with by superimposing a model of supply and/or exhaust fans to the natural ventilation model. The resulting whole model can account for interactions occurring between both systems.

The *natural ventilation model inputs* are the pressures provided by the generators, the model *parameters* are the apertures *K* coefficients and *n* exponents (6.1), and the model *outputs* are the air flow rates.

The *fan model input* can be the rotating speed that provides a relationship between fan air flow rate and fan total pressure (annex 5). The fan model equations can be merged with the natural ventilation model equations so that the location of the fan running point is an *output* resulting from the intersection between fan and building pressure/air flow rate curves.

The location of the fan running point allows the determination of the pressures and of the air flow rates in the whole model i.e. for the fans as well as for all the building natural ventilation entities (infiltration leaks, Controlled Supply Orifices, Transfer Orifices and Controlled Exhaust Orifices).

Two types of combined ventilation systems can be modelled in office buildings:

- Type C: natural air supply through Controlled Supply Orifices, natural air transfer through Transfer Orifices and fan powered air exhaust.

- Type D: fan powered air supply, air transfer through Transfer Orifices and fan powered air exhaust, with possible air heat recovery.

6.3.2.1. Modelling type C ventilation system in office buildings

Type C ventilation system can be modelled on fig. 6.6 scheme, which is similar to the natural ventilation scheme of fig. 6.5, with an exhaust fan added to the exhaust shaft. The building zones can be connected to the corridor through transfer orifices. A window model can be added to each branch connecting a zone with the outdoor (fig. 6.2).

The model can be used to simulate systems meant either for *air renewal* or for *free cooling* purpose.

In the first case, the corridor can be connected to a ventilation shaft through a grid aperture. An exhaust fan can be located on top of the vertical air duct, working during building occupancy hours.

When the model is used for free-cooling, the corridor can be connected to a specific ventilation shaft at each building floor, through a grid aperture. An exhaust fan can be located on the roof to perform free-cooling during the night, provided windows are opened as well as internal doors between offices and corridor. Each floor can be provided with its own free-cooling exhaust fan, which can be sized to reach an air renewal rate of 6 h^{-1} in the offices.

The model equations are listed in annex 6 §6.2.2.1.

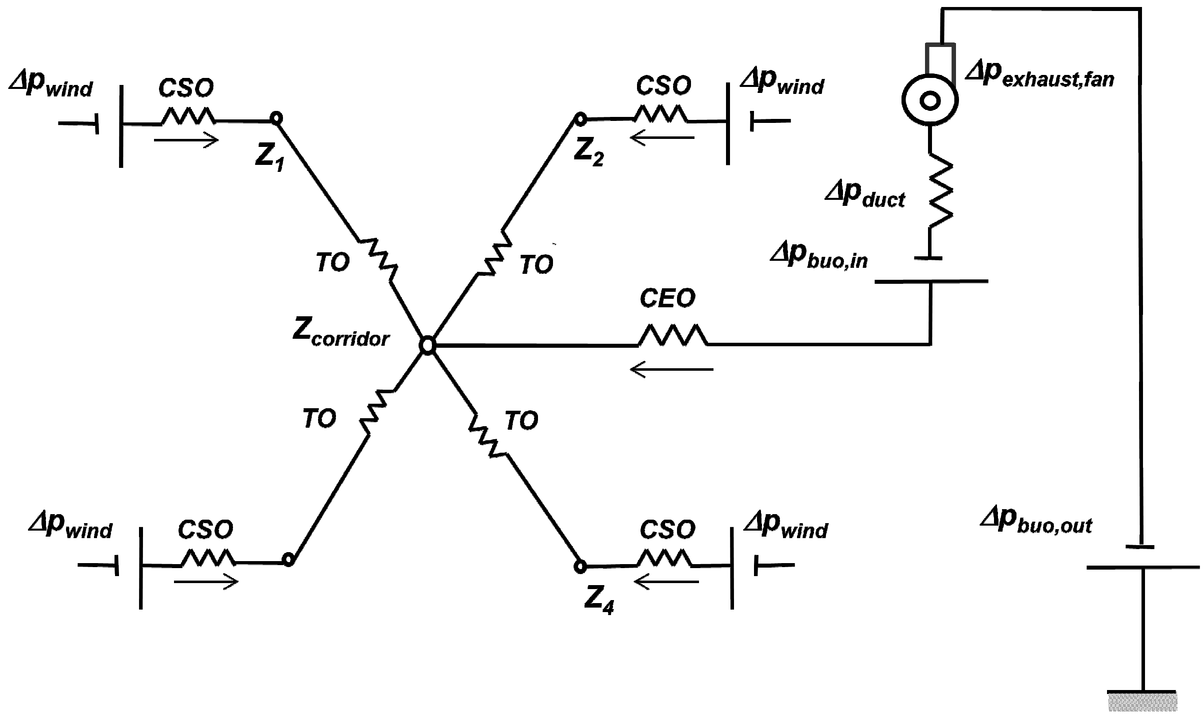


Fig. 6.6 Type C combined ventilation model including four zones and a corridor connected to an exhaust fan.

6.3.2.2. Modelling type D ventilation system in office buildings

Type D ventilation system generally includes two air ducts networks: one supplying air to the offices and one returning it from the offices to the outdoor. Modelling the system implies not only to model the supply and return fans, but also the whole air duct network. So a fan model and an air duct network model can be added to the natural ventilation model (see annexes 5 and 6). A heat recovery device and an Air Handling Unit can also complete the system.

As far as natural ventilation devices are concerned, air leakage can be maintained while Controlled Supply Orifices can be removed. The Controlled Exhaust Orifice and the exhaust ventilation shaft can be sized for a reduced air flow rate.

Type D system model is displayed on fig 6.6. The four offices natural ventilation model of fig. 6.5 is combined to the model of fig. 6.6 (with leakage instead of CSO) in order to build a whole combined type D ventilation model.

The model equations are listed in annex 6 §6.2.2.2.

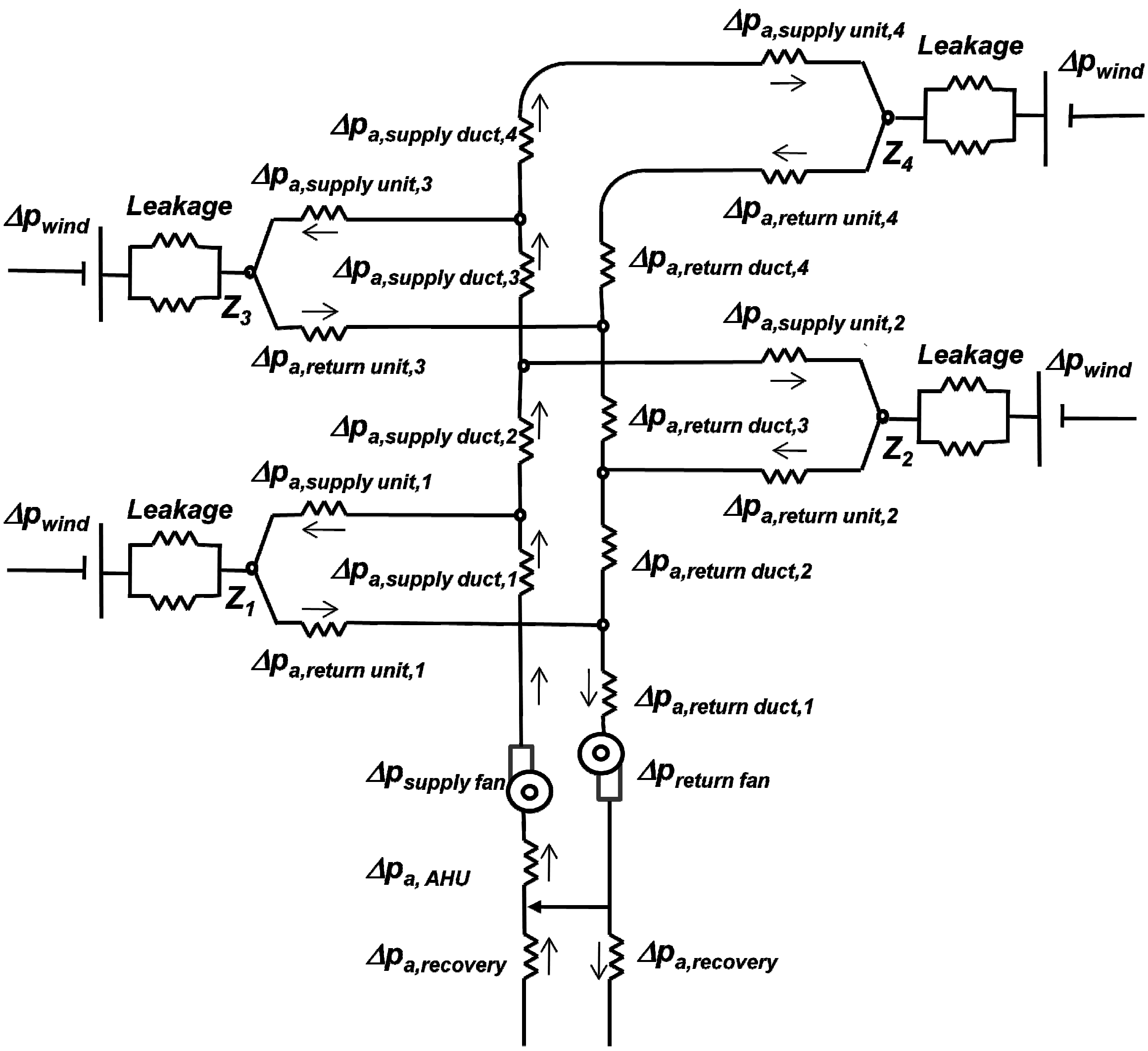


Fig. 6.7 Type D ventilation model including supply and return air ducts.

6.3.2.3. Fan running point

The fan model is presented in annex 5. The fan can be sized on the basis of a *nominal air flow rate*, equal to the sum of the nominal air flow rates corresponding to all delivered offices, and for a given *total pressure increase* compensating the maximum friction loss occurring when air is supplied to (or returned from) the different offices. Maximum friction loss generally occurs for the farthest delivered office. For given α_i coefficients, a fan rotation speed N and a fan diameter D can then be adopted, provided an optimal flow factor ϕ and an associated pressure factor ψ are given (annex 5 and 6 §6.2.2.3).

In OFF DESIGN conditions, the location of the fan running point is variable. For a given fan rotation speed, the fan running point depends on fan and building pressure/ air flow rate laws.

Combined together, fan model equations (annex 5) provide a relationship between *fan air flow rate* and *total fan pressure increase*, for a given fan rotation speed.

For given wind speed and associated pressure coefficients, and for given outdoor/indoor temperatures, the ventilation model (annex 6 §6.2.2.1 and 6.2.2.2) provides other relationships between *building and air ducts ventilation air flow rates* and *pressure drops* in the building natural ventilation devices, as well as in the duct network leading to the farthest office. They can be merged with fan model equations in order to find the fan running point for a given fan rotation speed. The fan total pressure increase as well as the fan air flow rates can be deduced from the location of that fan running point.

6.3.2.4. Air ducts modelling

Air ducts can be sized according to the *constant friction method*: the straight duct friction loss is constant in each duct slice. The main duct deserving the total nominal air flow rate can then be sized for a given air speed. The corresponding straight duct friction loss can be deduced, provided a duct roughness is given as model parameter (annex 6 §6.2.2.4).

A friction loss *K* coefficient can then be computed for the main duct conveying the total air flow rate (6.1). For other slices of ducts, a friction loss *K* coefficient can be deduced as function of the air flow rates ratio, as the design straight duct friction loss is constant (annex 6 §6.2.2.4).

Local friction losses occur when *diversions* or *confluences* exist. They can be expressed as function of the ratio of entering and leaving air speeds, which can itself be expressed as function of the air flow rates ratio (annex 6 §6.2.2.4).
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6.3.2.5. Network pressure balance

The design pressure drop can be computed as the maximum friction loss occurring when air is supplied to (or returned from) the different offices. It generally occurs for the farthest delivered office.

The *network pressure balance* can then be performed by adapting the friction loss *K* coefficient of offices air supply units, in order to reach the design pressure drop for each office deserving network branch (equation 6.1 and annex 6 §6.2.2.5).

6.4. Conclusion

A generic ventilation model can be applied to yield natural ventilation air flow rates in houses and office buildings. It can handle *natural entities* such as leakage, Controlled Supply Orifices, Transfer Orifices and Controlled Exhaust Orifices. A window stack effect can complete the model. The model can also handle *mechanical entities* such as air supply fans and air exhaust fans with their associated air duct systems. Natural and mechanical ventilation entities can interact with each other.

Fan powered air flows can be added either by imposing a given air flow rate (§ 6.2.3) or by introducing a fan model connected to an air duct network model (§ 6.3.2). In the latter case, fans and ducts can be sized in design air flows conditions, and a network pressure balance can be performed for those conditions, while a fan running point can be located in OFF DESIGN conditions.

The ventilation model can be associated to the building lumped model defined in chapter 5, in order to perform *indoor air quality analysis* as well as *thermal comfort* studies when free cooling strategy is used in summer conditions (chapters 7 and 8).