Ventilation system fire safety in the Xchange building

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Avdelningen för installationsteknik
Institutionen för bygg- och miljöteknologi
Lunds tekniska högskola
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Lunds Universitet

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Avdelningen för Installationsteknik tillhör institutionen för Bygg- och miljöteknologi på Lunds Tekniska Högskola, som utgör den tekniska fakulteten vid Lunds Universitet. Installationsteknik omfattar installationernas funktion vid påverkan av människor, verksamhet, byggnad och klimat. Forskningen har en systemanalytisk och metodutvecklande inriktning med syfte att utforma energieffektiva och funktionssäkra installationssystem och byggnader som ger bra inneklimat.
Nuvarande forskning innefattar bl a utveckling av metoder för utveckling av beräkningsmetoder för godtyckliga flödessystem, konvertering av direktelvärmda hus till alternativa värmesystem, vädring och ventilation i skolor, system för brandsäkerhet, alternativa sätt att förhindra rökspridning vid brand, installationernas belastning på yttre miljön, att betrakta byggnad och installationer som ett byggnadstekniskt system, analysera och beräkna inneklimatet i olika typer av byggnader, effekter av brukarnas beteende för energianvändning, reglering av golvvärmesystem, bestämning av luftflöden i byggnader med hjälp av spårgasmetod. Vi utvecklar även användbara projekteringsverktyg för energi och inomhusklimat, system för individuell energimätning i flerbostadshus samt olika analysverktyg för optimering av ventilationsanläggningar hos industrin.

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Abstract

The majority of the deaths when a fire takes place are due to the smoke. The fire gases can easily spread through the ventilation system if it is not properly designed and some safety measures are taken.

The current legislation suggest as solution to install independent ventilation systems or smoke barriers. However, the new Swedish legislation will offer new possibilities base on smoke dilution. While the smoke dilution is within a range of values the systems are safe and new design possibilities appear.

From this point of view, the ventilation system of the project Xchange from the company Skanska has been studied along this thesis. Both the risks from the possible smoke spread through the ventilation system and the opportunities it provides to extract the smoke are considered.

With the help of PFS, Program Flow System, different ventilation systems are tested in order to find a safe configuration that fulfills all the requirements set by the new legislation. The layouts are simulated under different fire conditions characteristics such as temperature, flow and position inside the building.

Before performing the simulations, the Xchange project is described and the present legislation and the fire smoke spread basics are studied. Also the implementation of the model in PFS is explained.

The results obtained from the simulations allow discussing the strong and weak points of each layout in order to decide what layout should be built.

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1. Introduction

1.1. Background

This Master Thesis is the final Project before obtaining the degree in Industrial Engineering intensification in Mechanical-Construction Sciences.

According to the courses I took during my degree and the background obtained from them I decided to write my Master Thesis about the ventilation system and its behaviour in case of fire.

On one hand building installations is one of the main working areas for a Construction Engineer and on the other hand, fire safety is quite an unknown subject in Spain so it is very interesting for me to go deep in it.

1.2. Aim

The majority of the deaths caused by a fire is due to the smoke. The inhalation of the toxic products contained in the smoke could lead to permanent damages in the health or even to the death. Moreover, smoke causes dizziness and fainting which makes difficult people to evacuate the buildings by themselves and the Fire Brigade's work which could lead to more fatalities.

Therefore it is very important to predict the behaviour of the smoke if a fire occurs and install the proper devices to guarantee the safety, the evacuation of the people and reducing the damages as far as possible. With this aim I have written this report. I have simulated different conditions and ventilation layouts to achieve the safest configuration.

1.3. Limitations

This thesis is based on the Xchange building. Although the theory and the method could be useful for further studies in other buildings, the results are only valid for this building. Some assumptions have been done in the calculations. These assumptions are explained in the different chapters and they must be taken into consideration.

1.4. Method

First of all, the legislation regarding the ventilation system in case of fire is studied to understand the legislation frame within this work is.

Then, the characteristics of the building are studied. It is necessary to know the demanded flows both for supply and exhaust and the architectonical characteristics of the building in order to understand the currently ventilation system and decide the possible alternatives.

The main ideas regarding fire smoke spread and the explanation of the dilution concept are also included in the report. It is important to know when fire smoke spread is likely to happen.

Finally, the different layouts are tested using PFS and the data is analyzed with Matlab. The results let to obtain some conclusions about which systems could be useful in a future for Xchange building.

2. Acknowledgement

First of all, I am really grateful to Lars Jensen, Head of the Building Services Department of the University of Lund for helping me and having been so patient with me during this time. Although he did not meet me before, he gave the opportunity of working with him from the first day. During these months he has done his best to lead my through this work, and I appreciate it very much.

Of course, I want to acknowledge my family to give me the chance of studying during all these years and especially this last year of my degree in Lund.

The ventilation system studied along this thesis owns to the Xchange building, a Skanska's project.

The 10th of February Lars Jensen and I hold a meeting with Lars Sjöberg part of the Xchange project. The main characteristics of the Xchange buildings were introduced by Lars Sjöberg, especially those related to the ventilation system. Both technical properties such as pressures or air flows and design characteristics like the system layout were shown during the meeting. Also the architectonical characteristics of the building were shown.

During the development of this work, Lars Sjöberg has provided me all the needed information to write this Thesis and he has helped me to solve and overcome the doubts which have appeared.

Therefore I want to acknowledge Skanska and especially Lars for his support during the carrying out of this work.

I would also want to acknowledge my professor Ignacio del Rey from Universidad Politécnica de Madrid. He has always tried to answer my doubts despite of being so far.

Last but not least, I want to be grateful to my partners during this year in Lund; thanks to their support I get to overcome the bad moments.

Sincerely,

Juanjo Blond.

3. Building code and main measures

The main rules and instructions gathered in the building codes regard the structural reliability and guarantee the evacuation in case of fire. The spread of the fire and the smoke must be avoided both internally in the building and to the adjacent buildings.

The consulted codes to write this Chapter have been the Spanish and the Swedish code. There are some similarities but the different ways to build in each country lead to some difference in the codes.

Keeping to the topic of this Thesis, the Swedish Building Code gathers some points about the ventilation and the spread of gases through the ventilation systems for dwellings while in the Spanish code it only deals with the ventilation for garages or malls. According to the Spanish code, in order to design the exhaust system and how it should work in case of fire the standard UNE 23585-2004, which European correspondence is the standard EN 12101-5, must be applied.

The importance of the ventilation system as part of the fire safety system is clearly set in the Swedish code:
Buildings or parts of buildings should not be put into service until ventilation systems and technical fire-protection installations are ready for use. (BBR 2006:22, General Rules for Buildings, 2:52).

3.1. Fire compartment

According to the Swedish Building Code a *fire cell* or a *fire compartment* is:

The term fire compartment refers to a part of a building separated from other parts of the building, inside which it is possible for fire, during a prescribed least period of time, to develop without spreading to other parts of the building.
The fire compartment shall be separated from the rest of the building, by enclosing walls and floor or in some other way, so that escape from the building is secured and so that persons in adjoining fire compartments or buildings are protected during the prescribed period of time. (BFS 2002:19, Safety in case of fire, 5:232)

The buildings must be divided into fire cells to contain the fire and the smoke spread during a certain period of time *(BFS 2002:19, Safety in case of fire, 5:6)*. Dwellings are class Br 1 buildings; this means that both structural and non-structural elements must be at least EI 60 category. All the envelope of the fire cell should fulfill this instruction even though doors, windows and glazed balconies may have the half category but not lower than EI 30.

The envelope of the fire cell can also be delimited by active smoke barriers which are usually hide and work only when the fire is detected. These smoke barriers must fulfill the same characteristics as the rest of the boundary elements. The fire cell cannot include areas in more than two storeys.

The ventilation system is part of the fire cell so the same regulations deal with it. The materials used in the duct must be the same category than the rest of materials used in the fire cell.

In this report, each apartment is regarded like a fire cell. As it can see in the drawings both partitions and doors agree the law. The common wall between the apartments in each flat is EI 60 and the entrance doors EI 30:

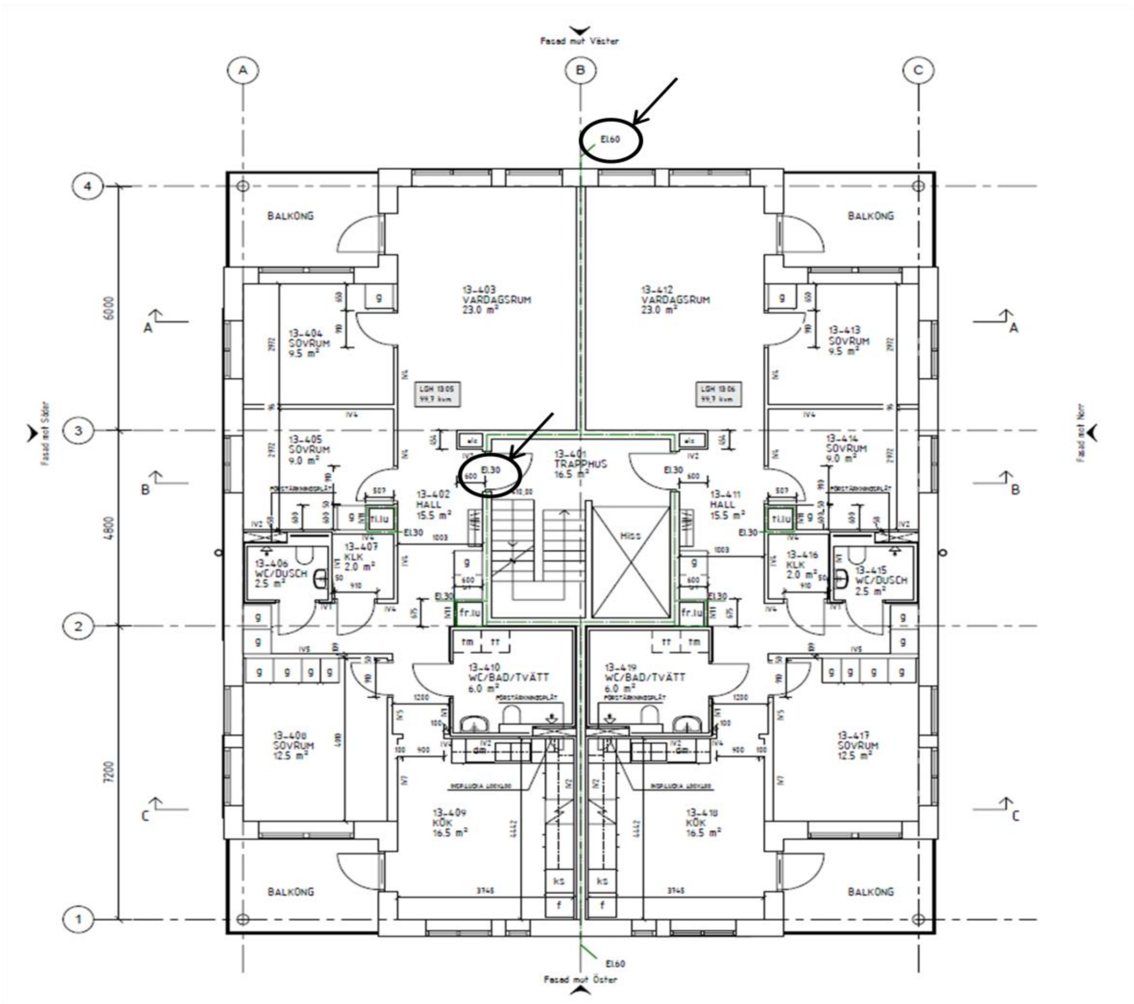


Figure 3.1 . Partitions fire resistance. Picture taken from drawing A40.1-134

3.2. Smoke or countercurrent supply air dampers for each apartment

A satisfactory protection against the spread of smoke must be provided for each fire cell. As it has been said before, the ventilation system is part of the fire cell and it must guarantee the control of the smoke.

One possibility to ensure this point is to install smoke dampers in each fire cell. If this is the case, the damper becomes part of the envelope of the fire cell and it must satisfy the same properties than the rest of it.

The European Standard EN-12101:5 distinguishes between two possibilities, if the supply-exhaust system is regarded like part of the ventilation system in case of fire or it is just a heating air conditioning system. The Standard states norms for the second possibility.

In this case, the system must be shut down and the smoke spread must be avoided installing dampers which should operate automatically and at the same time as the system shuts down (*EN-12101:5 or UNE 25585:2004, Fire Safety. Smoke and Heat Control System, 7.7.2).*

3.3. Pressure relief to outside of apartments or duct systems

An alternative measure to avoid the fire and smoke spread through the building is providing special pressure relief devices such as windows or ducts.

This solution is especially suitable for basements, stairways and attics or storage rooms and it is regulated by the law.

The smoke vents for the basements should have an area equal to 0.5% of the local space or 0.1% if there are water sprinklers.

Stairways ought to be equipped with windows or other devices in each storey to control the gases. Rescue services shall operate them.

The storage rooms must be provided with ventilation areas equal to the 1% of the room's area. It shall be possible to open or break the windows or panels used for ventilation from the outside

3.4. Running ventilation system with or without safety measures

The safest way to avoid the smoke spread through the ventilation system is providing independent systems for each fire compartment. Obviously, this is not always possible; therefore it is important to decide how the system should work in case of fire.
The Swedish Building Code says:

Satisfactory protection against the spread of fire gases may be obtained by:
Allowing fire gases to enter the ventilation system but designing the system in such a way that the spread of fire gases between fire compartments is prevented or considerably impeded depending on the design and the nature of the premises. The spread of fire gases should be prevented for escape routes and bedrooms.

The handling of this smoke is not regulated by the Code, it does not say how much smoke can spread through the ventilation system and how much of it can enter in the different fire cells.

As it has been said, European Standard distinguishes between the ventilation system and the smoke ventilation system. The ventilation system must be shut down and the smoke spread through it avoided.

4. Description of the multifamily house

Skanska Company has designed some buildings under the Xchange name which should be suitable to be built any place in Norway, Finland or Sweden. The aim is to have a basic project which satisfy the user's needs and which could be built easily, quickly and economically.

Different configurations of the dwellings have been done and the multifamily dwelling study in this Master Thesis is one of them: an eight flats (including the basement and the roof) building with two dwellings in each one and some commercial spaces in the ground floor.

4.1. Measures of the buildings

The building is rectangular. The distances between pillars are 14.4 m for the east and west facade and 18 m for the north and south one.

The building is 24.35 m height. The first flat is 1.8 m above the reference level, from this flat each three meters we can find a new level:

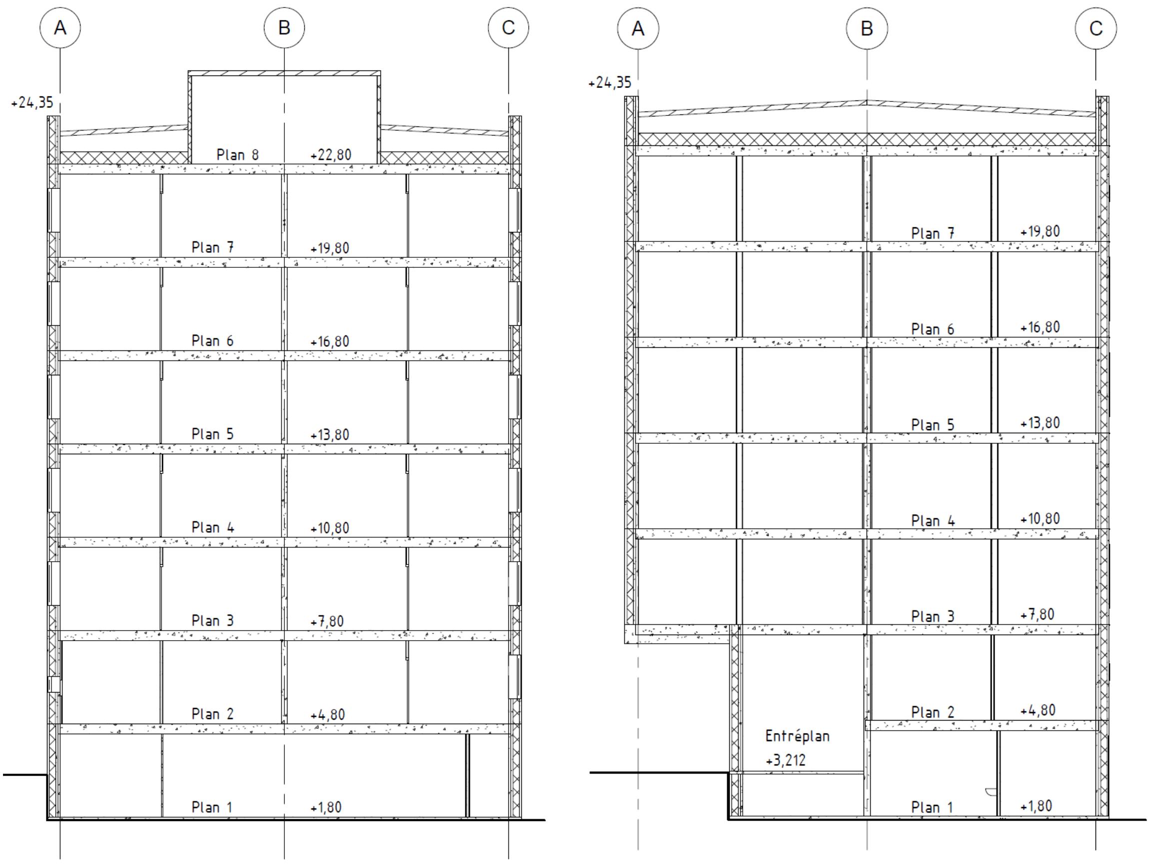


Figure 4.1. Building height. Pictures taken from A40.2-131 drawing

Flat level	Height from the reference level (m)
Ground Floor (Plan 1)	1.8
First (Plan 2)	4.8
Second (Plan 3)	7.8
Third (Plan 4)	10.8
Fourth (Plan 5)	13.8
Fifth (Plan 6)	16.8
Sixth (Plan 7)	19.8
Seventh (Plan 8)	22.8

Table 4.1. Storeys height

The difference between the seventh floor and the total height of the building is due to a wall that surrounds the perimeter to avoid accidents in case of any one has to stay in the roof.

The distribution of the dwellings from the second to the sixth floor is the same, 99.7 m^2 spread according to the following table:

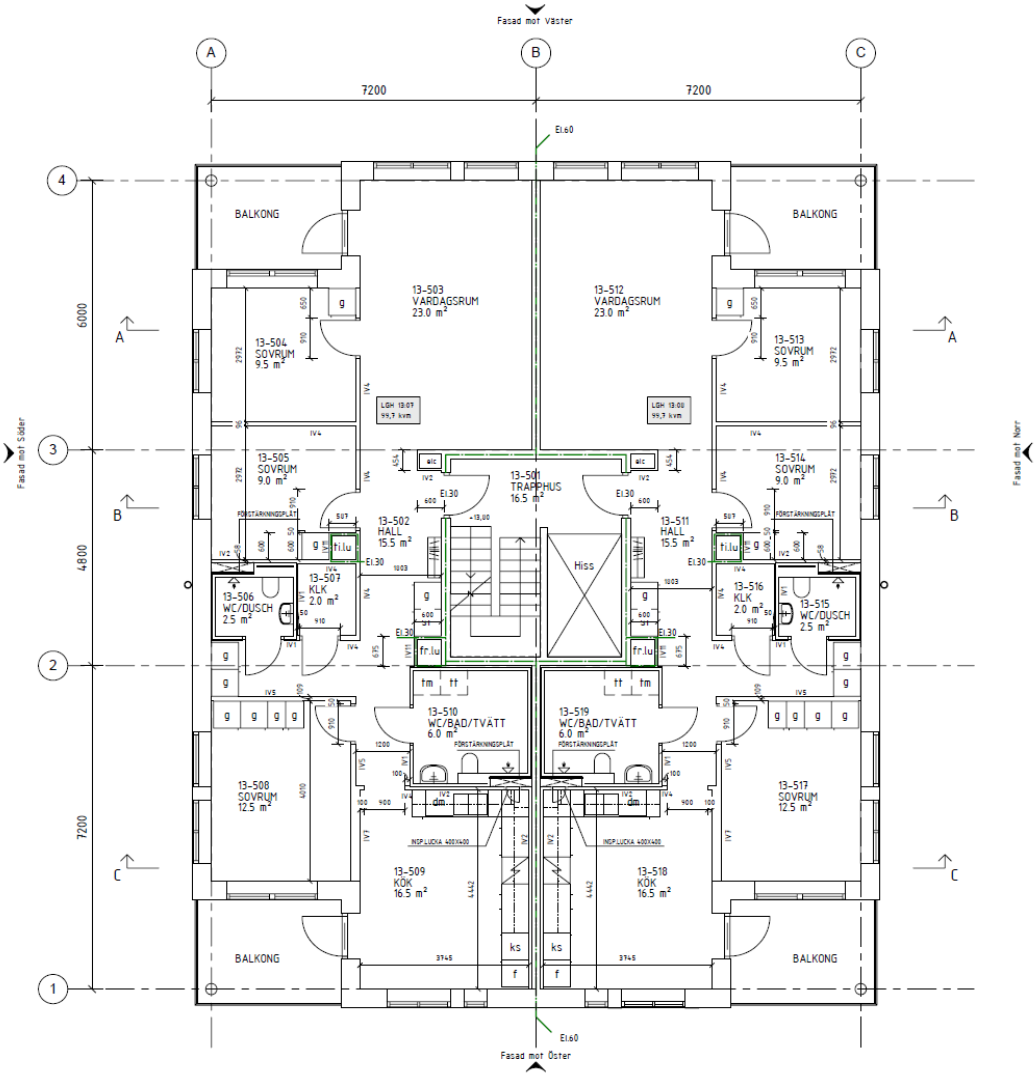


Figure 4.2. Distribution of the standard flat. Drawing corresponding to the fifth floor. Picture taken from A40.1-135 drawing

Room	**Area (m^2)**
Living room	23.0
Bedroom 1	9.5
Bedroom 2	9.0
Main bedroom	12.5
Bathroom 1	6.0
Bathroom 2	2.5
Kitchen	16.5
Hall	15.5
Clothes Closet	2.0
Total	**96.5**

Table 4.2. Area of the different rooms

3.2 m^2 are occupied by the inner walls and facilities.

The dwellings placed in the first level are different. The entrance of the building and some facilities occupy part of this level and consequently they are smaller than the rest.

There is one 63.1 m^2 apartment with a living room of 23 m^2, a single bedroom of 15 m^2, a kitchen of 11.2 m^2, a bathroom of 6m^2 and a hall of 6 m^2.

The other one is like the normal apartment, it has 97.8 m^2, but it only has the main bathroom and the main room is little bigger (14 m^2 instead of 12.5 m^2):

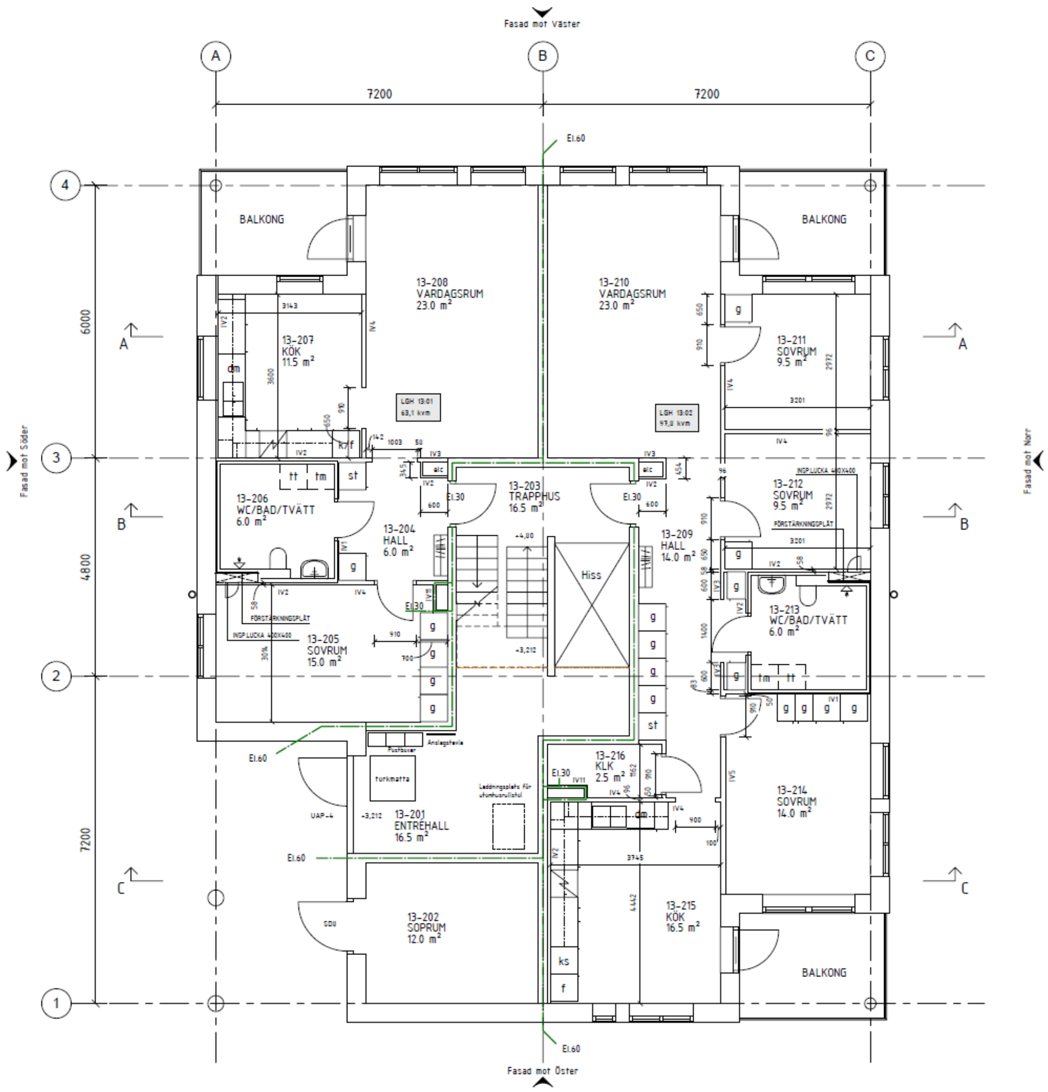


Figure 4.3. First floor apartments. Picture taken from A40.1-132 drawing

The floors have a 3 m high but they are separated by 0.4 m of hollow concrete to guarantee the isolation between the apartments, so only 2.6 m are free. The Swedish building code establishes that at least the high of the building must be 2.40 m (*BFS 2002:19, Building Regulations, Section 3 Design 3:11*). In this case, this minimum height has been used has reference and the other 0.2 m have been left free to use them for installations (air supply, electricity, etc.)

4.2. Building divisions

As it has been established in the previous point, the building has eight storeys.

The apartments are between the second and the seventh floor which means that there are a total of twelve living spaces.

The ground floor host the entrance from the street, twelve store rooms (one for each dwelling) and a commercial local. Also, there are two rooms dedicated to the building facilities. One of the rooms contains the electrical equipment and the other one the district heating substation.
The commercial local consists of three rooms and two bathrooms. It has a single entrance from the street and all the rooms have windows.

The access to the dwellings is provided by a lift and stairs placed in the central position of the building.

The flats are internally divided into two symmetrical dwelling, *Figure 4.2. Distribution of the standard flat*. Each dwelling has it owns kitchen, one bathroom, one toilet (without shower), three bedrooms and a living room. In addition, in the corners there are two balconies.

The distribution of the different rooms inside the apartment is done to reduce the amount and the complexity of the installations. The kitchen and the main bathroom are the spaces which require the majority of the installations so they are placed sharing a wall. The symmetry of the dwellings also makes this purpose easier. Thanks to this layout, some money is saved and some space can be used for the living space instead for the installations. The kitchens and bathrooms of both apartments share the same duct and the length of the connection elements is reduced.

The seventh floor (the roof) is devoted to the Air Handling Unit (AHU) which is responsible for all the air circulation inside the building. This unit and the ventilation system are described in the point *5.1 Air Handling Unit description, page 19*:

4.3. Materials and components

According to the initial aim of the Xchange project, the buildings are constructed using prefabricated concrete elements which allow a fast progress of the work and a significant reduction of the price. The prefabricated elements technology is well known in Nordic countries satisfying an important objective, the project can be lead in all of them.

The most of the materials used in the buildings are prefabricated. Currently, concrete prefabricated panels are very common because of they allow a quickly progress of the building works and they offer high quality during their life period.

Thirteen different prefabricated panels are used for the divisions. Depending on the spaces the panel divides it must satisfy certain characteristics such as fire resistance or noise dumper. For example the internal walls are EI 30 while the panels dividing the dwellings must be EI 60 to agree the law *Figure 3.1. Partitions fire resistance, page 10.* The slabs between floors are also done using prefabricated elements.

This philosophy leads to the use of prefabricated bathroom modules. A cabin with a pre-installed supply and waste water pipes, electrical cables and exhaust air ducts is used. Only the needed connections to the building facilities have to been done in site. The use of these prefabricated cabins must be taken into consideration when designing the building, the access for connecting the installations must be provided.

The structure used for the building is made of concrete.

5. Description of the ventilation system

The main study issue of this Master Thesis is the ventilation system in case of fire in an apartment. In Nordic countries, the ventilation system is very important facility. The hard weather that these countries have to face requires properly design of the system both to satisfy legislation and achieve the level of comfort demanded. In addition, a good design can recover much heat from the exhaust air and deliver it to the incoming air flow saving much money.

Furthermore, this system plays a very important role in case of fire. The majority of the deaths caused by a fire are due to the smoke spread. Therefore, it is very important to guarantee the working of the ventilation system and to know how it will performance in case of fire.

The importance of this system is gathered in the Swedish Building Code which says *"Buildings or parts of buildings should not be put into service until ventilation systems and technical fire-protection installations are ready for use" (BBR 2006, Section 2: General Rules for Buildings, Technical fire protection installations and ventilation systems, 2:52)*

5.1. Air Handling Unit description

The main air handling unit, (AHU) is on the roof of the building at the eighth floor. The AHU provides air to the apartments, the store rooms, the electrical unit, the district heating substation, and the common spaces (lift and stairs); also extract the air from this spaces and the garbage room. There is another AHU unit in the second story which supplies and exhausts air from the commercial space situated in the ground floor but it is out of the targets of this Thesis.

The AHU unit is a prefabricated cabin of 16.5 m^2, equipped with all the technical equipment necessary for the ventilation. The unit would be lifted to the roof with a crane; some hooks are incorporated for its installation.

In the outside, all the connections for the supply and exhaust air are provided, as well as the connections for the cold and hot water, heating water for the radiator, electricity supply, floor drain and an alarm point.

Inside, all the AHU equipment is placed, such as: the supply and exhaust fans, the air filters, the air heater or the heat exchanger. Secondary equipment, but not least important, for the AHU working is also placed inside: the connection ducts, a radiator, or all the electrical installations for the AHU unit working are fitted inside.

Both the supply and the exhaust fans must operate continuously. The speed of them is controlled with pressure controllers placed in the exit of the supply fan and the entrance of the exhaust fan from the heat exchanger.

The AHU must handle 610 l/s of air flow both for the supply and exhaust system working under standard conditions. In case of emergency, the AHU must be capable of extract till 810 l/s.

The heat exchanger, a plate type one, recovers the heat from the exhaust air and delivers it to the supply air. The temperature of the supply air can be 21 ºC and it is designed to deal with and outside temperature of -20 ºC. It is capable of recovering until 81% of the exhaust heat. The rest of the heat will be provided from the air heater.

Furthermore, there is a radiator to ensure a 10 ºC temperature in the room. It will deal with water between 45-60 ºC to deliver 1000 W. A thermostatic valve guarantees the desired temperature.

As it has been said before, it is important to save energy in the system; it must be recovered as much heat as possible. In addition, this system must be designed to work under very hard conditions (-21 ºC outside operating temperature). Regarding this purpose, the AHU cabin is insulated and the heat transfer coefficients (U-values) must be below 0.4 W/m^2K for the walls and 0.3 W/m^2K for the roof.

Also, the air ducts, both supply and exhaust, are insulated. They have a 50 mm heating insulation and 50 mm condensation insulation.

Moreover, the watertightness of the cabin must be guaranteed.

Finally, the system must be silencing. The fans are internally insulated against vibrations and the walls of the cabin dampen the noise.

5.2. Materials used in the components

The cabin is constructed with sandwich panels made of a layer of insulation wool between two zinc plated steel sheets. The ducts used in this installation are also made of zinc plated steel.

5.3. Behavior in case of fire

The Xchange building is provided with a converted ventilation system to prevent the spread of the smoke. This means that in case of fire the supply system is also used to exhaust the fire gases The system is designed to stop the supply air fan in case of fire. In the chapter 8, *Fire Smoke Spreads Simulations,* this layout and some others are studied.

The exhaust fan must operate in case of fire. It has to be working during an hour with an expected temperature for the exhaust gases of 67 ºC. During a fire, the speed of this fan should increase in order to exhaust more fire gases.

The system built is a conversion type one. There is a by-pass duct which avoids the pass of the air through the heat exchanger to prevent any damage on it. In fact, this by-pass connects the supply ducts with the exhaust fan making it possible to use them like exhaust system too.

The ventilation system must work in case of fire. There are fire smoke dampers placed in the exhaust ducts connected to the rooms where a fire is more likely to happen or those which should be especially protected. These rooms are the electrical room, the garbage room and the stairs to guarantee the evacuation if it would be necessary. The supply air duct to the electrical room has also an anti smoke spread damper.

5.4. Behavior in case of freezing

The Xchange building is designed to be built in the Nordic countries. This means that the weather is an important factor.

Regarding the ventilation system, it must be protected for freezing. The ducts are insulated and in the AHU cabin there is a radiator which must keep the room temperature at 10 ºC.

In case of freezing risk the fans are stopped and the damper between the supply fan and the heat exchanger is also closed.

The air is taken from a different duct and it is pre-heated before putting it into the supply system. The supply air is by-passed in order to limit the drop in the exhaust air temperature to prevent heat exchanger from freezing.

5.5. Supply system layout

The supply air system has two main ducts, one branch for the left flats and the other for the right ones. One of the branches also provides air to the electrical and the storage rooms. The main ducts cross the building all the building height along.

Each flat is connected to its correspondent branch. The bedrooms and the living room are the spaces which must be provided with fresh air.

The connection with the main ducts is done in a bedroom and it is hidden inside a wardrobe. A silencer is placed before the distribution box which is situated in the hall ceiling. The supply ducts for each room are connected to this distribution box.

The main ducts have a diameter of 400 mm along all their length. The duct that connects the main duct with the distribution box has 160 mm of diameter and 1 m length. The distribution ducts are 100 mm for the bedrooms and 125 mm for the living room.

Room	Duct size (mm)	Length (m)
Bedroom 1	100	6.5
Bedroom 2	100	1
Bedroom 3	100	3
Living room	125	1

Table 5.1. Diameter and length of the supplier ducts.

The connection box measures 200x200 mm just the free space available in the ceiling.

Except one, all the rooms which need air supply have entrance from the hall so the ducts are led through the ceiling of it. There is one room which has entrance from the living room and its supply duct is led through another room.

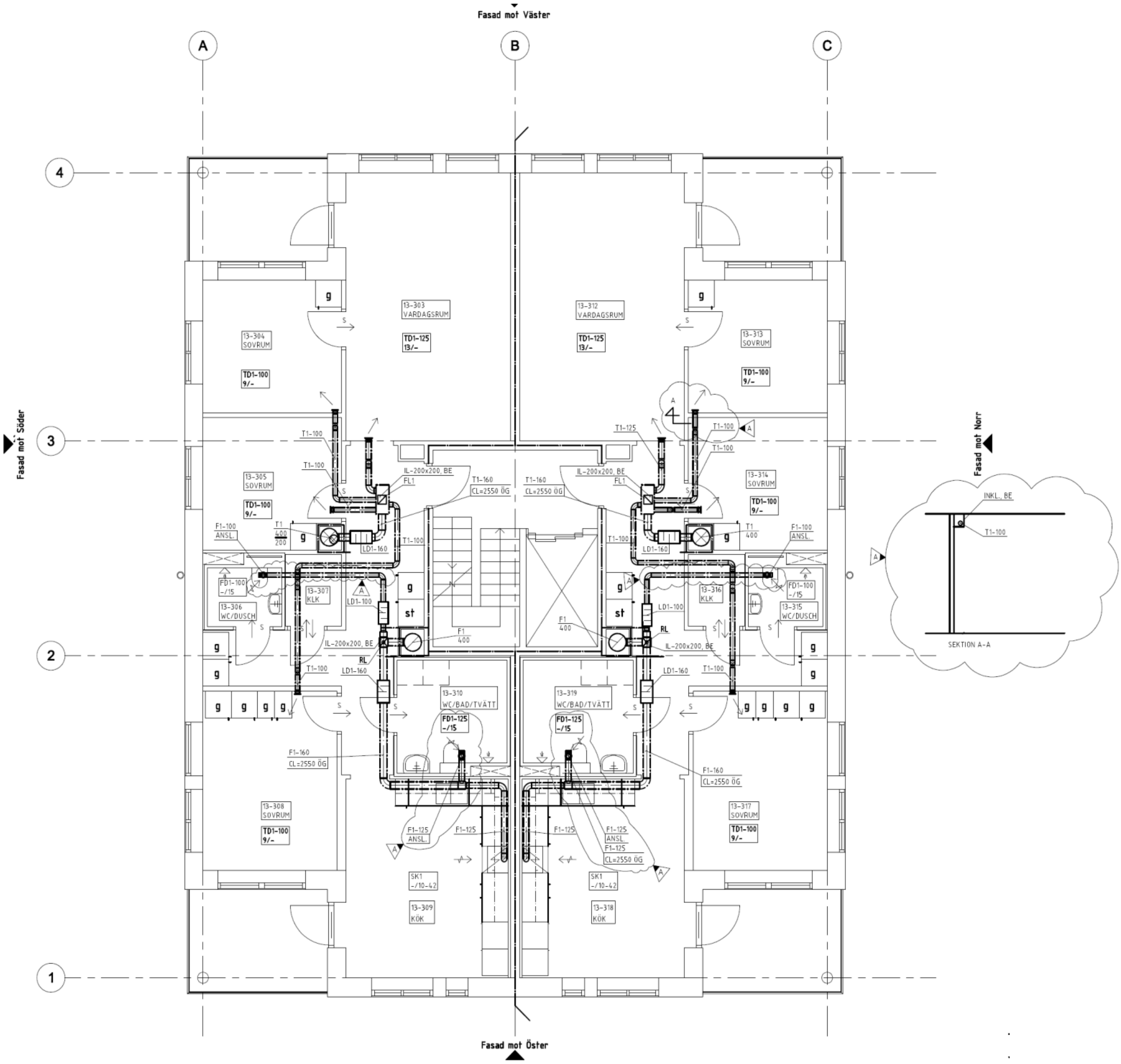


Figure 5.1. Ventilation layout inside the apartment. Picture taken from V57.1-133 drawing.

The volume of air which should be supplied to the different rooms are listed in the following table:

Room	Flow (l/s)
Bedroom 1	9
Bedroom 2	9
Bedroom 3	9
Living room	13
Total (per apartment)	40

Table 5.2. Litres per second supplied to each room

These values are a little oversized. The volume estimated for the living room is 59.3 m^3 (3.8x6x2.6 m) and the flow for this area is 13 l/s, which turns a figure of 0.78 -/h. The design figure is 0.5 -/h, lower than the number used in this case. The Swedish Building Code establishes that the minimum supply flow must be 0.35 $l/s \cdot m^2$ *(BBR 2006:22, Section 6: Hygiene, Health and Environment, Ventilation Flow, 6:251)*. Using this figure, the air supplied should be 8 l/s but considering that not all the rooms have supply devices for total area of the flat it should be 35 l/s, a value a little lower than the one used.

The rooms do not have the same area but, all the ducts have the same size and the flow supplied has been fixed the same.

The area of the living room is bigger than the bedrooms ones, so the flow provided is bigger.

5.6. Exhaust system layout

Like in the supply system there is one branch for each side of the building. In addition, one of the branches exhausts air from the electrical room, the storage rooms and the stairs.

Inside the apartments, the bathroom, the shower room and the kitchen must be equipped with air exhaust system.

The connection is done with the main duct in the hall, near the entrance door. Close to the connection there is a distribution box from which two ducts leave. The connection box measures 200x200 mm, like the supply one, the limit to fit in the ceiling.

Each branch has its own silencer. The silencer of the shower room has a dimension of 100 mm whereas the other branch measures 160 mm.

One of the ducts reaches the shower room and the other one the bathroom and the kitchen. In this last one, when it gets to the bathroom a duct is led to this room, while another continues to the kitchen.

The shower room duct measures 100 mm. The common duct for bathroom and kitchen measures 160 mm and, once it is split the independent ducts measures 125 mm.

Room	**Duct size (mm)**	**Length (m)**
Shower room	100	4
Common duct (kitchen and bathroom)	160	7
Kitchen	125	2.5
Bathroom	125	0.5

Table 5.3. Diameter and length of the exhauster ducts

The litres of air which should be extracted from the different rooms are gathered in the following table:

Room	**Litres/sec (l/s)**
Bathroom	15
Shower room	15
Kitchen	10-42
Total (per apartment)	40-72

Table 5.4. Litres per second extracted from each room

Reading the values of the table, and comparing them with the supply system values, we can see that in normal operating conditions the litres supplied and the litres extracted are balanced (40 l/s).

The litres which could be exhausted from the kitchen can vary. When cooking some smoke can be produced and an extra capacity of extraction is needed.

6. Fire smoke spread basics

Previously studying some important points about smoke spread, some concepts must be defined.

The maximum power of the fire does not go directly to the smoke. The heat from the flame is transferred to the surroundings by convection and radiation. This means that, for example, the walls of the room absorb some heat.

Consequently, we should distinguish between the theoretical, 3000 kJ/m^3_{dryair}, and the practical heat, 1500 kJ/m^3_{dryair}, that can be released by the oxygen. It is interesting to regard the units of these parameters which are in kJ/m^3_{dryair} consequently the amount of heat depends on the available dry air “to be burnt”. This point is quite important because fresh air sources like windows or leakages may increase the dangerous of a fire.

The studied case is a fire in an apartment with all the doors open; the whole dwelling is considered like a single volume. Moreover, there are windows, doors or leakages which connect the room with the rest of the building and the outside.

This means that the pressure is regarded like a constant boundary condition which value is 1 bar. If the pressure inside the burning room exceeds this value, there will be a flow in order to keep the pressure constant.

6.1. Rule of thumb for fire flow and fire volume

As it has been establish before, the pressure is a constant value of the system, 1 bar, so, the volume and the flow will be influenced by the temperature reached during the fire.

The inner volume in the room is also constant. The walls are supposed not to fall down so the room volume, V_{room}, will not change and a temperature T_1 is measured.

Using the ideal gases equation, $p \cdot V = nRT$, the volume initial volume would be $V_1 = nRT_1/p = V_{room}$ and, in a certain instant with a temperature T_2, it would be $V_2 = nRT_2/p$.

Dividing both volumes, we obtain that $V_2 = V_1\,(T_2/T_1) = V_{room}\,(T_2/T_1)$, a volume higher than the maximum which the room could contain. This excess of volume must leave the room. Dividing it by the time it takes for the temperature change we obtain the average flow:

$$q_{as} = V_{room}\,(T_2 / T_1 - 1) / (t_2 - t_1)\ \ (m^3/s)$$

On the other hand, we may consider and instantaneous flow depending on the fire power:

$$q_i = R \cdot P / p \cdot c_p \cdot M$$

R=Gases constant (J/kmol K)
P=Fire power (W)
p=Pressure (Pa)
c_p=Specific heat capacity (J/kg K)
M= Molecular mass (kg/kmol)

Considering the losses under normal conditions (p=1 bar), we may set like a rule of thumb that each 1 MW of heat generates 1 m^3/s of smoke.

6.2. Rule of thumb for window breakage

The breakage of a window is a critical parameter for the development of a fire. It is a source of fresh air for the fire and the hot gases can reach other points of the building spreading the flames. Because of its importance, several experiments have been carried out about this issue. The literature read for this chapter is listed in the chapter 10 *References* (page 87) with the numbers [10], [12] and [13].

As we have said, the pressure is regarded like a constant parameter so the critical factor which causes the glass crash is the temperature gradient. The heat reaches the window in two different ways by convection and by radiation, though glass is almost transparent for radiation. Glass is a relative poor thermal conductor so much of the energy is storage in the glass raising its temperature.

The windows have their edges framed so the expansion is blocked. In addition, the frames are usually metallic which means that the thermal coefficient is higher and they allow evacuating energy through them. This creates a temperature gradient between the centre (hot) and the sides of the windows (cold) which causes stresses in the glass.

The stresses follow the Hook's law:

$$\sigma = \beta\, E\, \Delta T$$

σ= Stress (Pa)
β= Thermal coefficient of linear expansion (normal value: $8{\cdot}10^{-6}$ $^{o}C^{-1}$)
E = Young's modulus (normal value: 80 GPa)
ΔT= Temperature gradient (ºC)

If $\sigma > \sigma_e$ the window will crack. This does not mean that the window will break; this will happen if the temperature of the rooms continues rising.

After analysing the literature, some values can be set to establish a work frame:

- A 90 degrees temperature difference between two points of the windows leads to glass crash.
- Window glazing crashes when the temperature of the room is between 200-400ºC.
- Real values are uncertainly. The temperature difference between the upper gas and the lower gas my lead higher stresses.
- The first cracks appear near the frame. In this region the temperature gradient is bigger than in the rest of the window.

Another factor that could break the window is the pressure. According to the literature an overpressure around 5 kPa will cause the glass breakage.

6.3. Rules of thumb of building pressure breakage

Several materials and construction techniques are used nowadays. These factors make it difficult to provide a very accurate range of values for pressure breakage.

It is important to distinguish between the inner and the outer panels, as well as the different possibilities to build them. Prefabricated concrete panels are going to be considered as reference because they are used for Xchange buildings.

Many different panels are used for inner walls. Like we are taking the inner space as a whole the fall of one of them will not affect our calculations so their resistance will not be studied.

The façade walls have a width of 400 mm. The panels are made with different layer including noise, airtightness or thermal isolation barriers. The stiffness of these layers can be neglected when comparing with the concrete one, so it will be neglected in calculations.

The resultant load due to the fire pressure will be considered like constant both for the height (H) and the width (L) of the wall. Although the gases are stratified due to the temperature difference, this is very small and the constant assumption is valid. The over pressure along the height of the room is in a range of 10 Pa.

The study has been carried out for the less favourable panel and situations. The one with the largest area (H=2.5 m and L=5 m) is the most dangerous because the loads and moments that both panels and screws have to face are the biggest. Also, the unique supporting elements which have been taken into consideration are four screws in the corners.

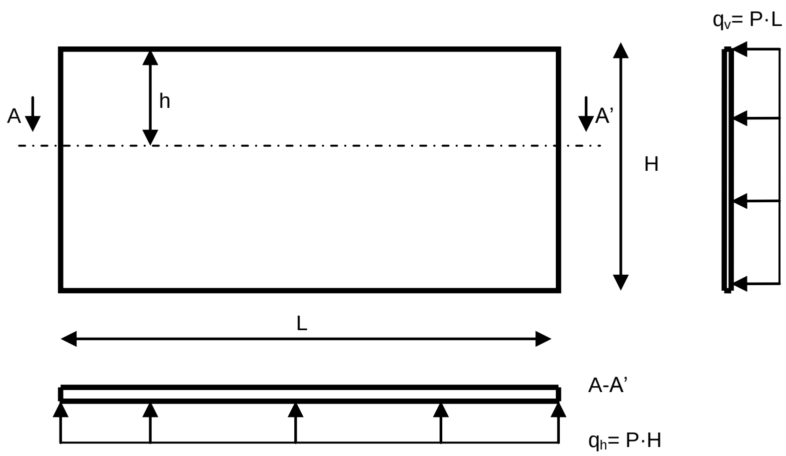


Figure 6.1. Load due to the pressure in the facade panel

The real failure values will be higher than the calculated ones but, designing this way, we are guaranteeing a range of safety for the façade failure.

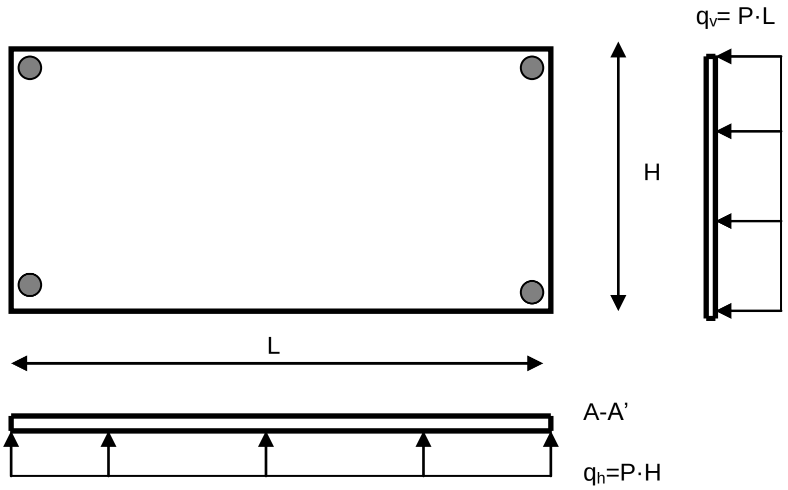


Figure 6.2. Panel screws.

Two possible failures can be studied: the panel itself failure due to an excess of pressure caused by the expansion of the gases or the supporting elements failure.

Dealing with the panels, the main problem could be caused by the bending moment. Each force creates one moment but in different axis. The maximum moments are reached in the middle of the panels and the values are:

$$\text{Vertical load} \rightarrow q_v H^2 / 8 = PLH^2 / 8$$
$$\text{Horizontal load} \rightarrow q_h L^2 / 8 = PHL^2 / 8$$

The panels are made of different layers but the resistance materials are concrete and steel. Concrete has poor properties when working at traction; therefore, these panels usually are reinforced with steel to improve their characteristics in this area. Assuming identical characteristics in both bending directions, the most dangerous bending is created by the horizontal load in the middle of the panel. The possible failure is caused in the traction side of the panel, in this case the outer side of it.

A very rough estimation of the pressure which these walls can manage has been done as follows:

As it has been said, concrete has very poor traction properties so for the calculations only the steel is considered to work. A square mesh of 200 mm made of steel bars with 6 mm of diameter is considered inside the panel.

Each wire should resist the load corresponding a square of 200x200 mm^2 of the mesh:

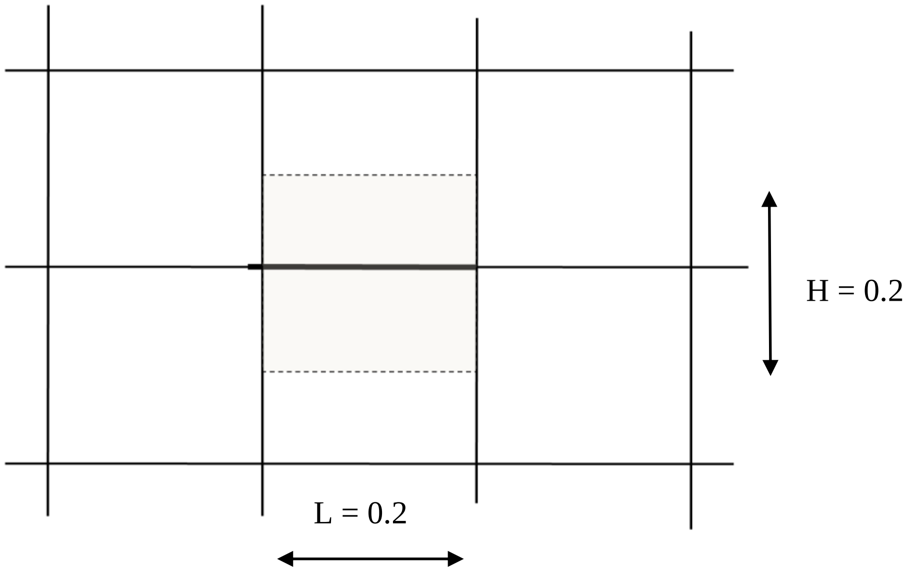


Figure 6.3. Load in the mesh

The maximum bending moment in a wire is:

$$\sigma_{max} = M_f / W_{min}$$

$$\sigma_{max} = 500\ MPa$$
$$W_{min} = \pi R^3/4$$

Performing the calculations the maximum pressure is:

$$\sigma_{max} = M_f / W_{min} = \frac{PHL^2 / 8}{\pi R^3/4}$$

$$P = \frac{\sigma_{max} \cdot \pi R^3/4}{HL^2 / 8} = 10.602\ Pa$$

This calculation is very rough, because it has not been considered the work of the panel like a plate and the cooperation of the different materials but it gives a reference value.

On the other hand, the pressure in the wall may cause the failure of the supporting elements. As it has been established previously, only four screws in the corners of the panel has been considered. This is a very simplified model which leads to a reference value; usually, more screws or hooks are used so the stress that each one has to manage will be lower and more pressure could be resisted.

Assuming that the screws are made of steel in order to fail the pressure should be:

$$Total\ load \rightarrow P{\cdot}H{\cdot}L$$

$$Load\ in\ each\ element \rightarrow P{\cdot}H{\cdot}L\ /\ 4$$

$$D_{screw} \approx 1cm$$

$$\sigma_{adm} = 500\ MPa$$

$$PLH\ /\ 4 = A_{screw}\ \sigma_{adm}$$

$$\Delta P \approx 12.566\ Pa$$

To get this pressure, assuming that the apartment is absolutely air tightness, the air temperature should raise 37º C from the normal temperature. There are around 250 m^3 in the apartment, so around 8 MJ would be necessary to reach the critical temperature supposing that there is not any heat loss.

At this pressure a door (2 x 1 m) would have to handle a load around 25000 N or 2.5 tons and a window (1.5 x 1.5 m) around 28000 N or 2.8 tons, so it is realistic to think that the door or the windows will break before the panel.

6.4. Rule of thumb of building leakage

Due to the building process there are leakages in all dwellings. Buildings are not air tightness and some smoke spread through these cracks as well as some air can go inside the room through them.

As well as in the previous point *"Rules of thumb of building pressure breakage"* different techniques and materials provide very different values.

Four different areas can be regarded as leakages, supply area A_s (m^2), exhaust area A_e (m^2), and inner and outer leakages areas A_i (m^2), doorways gaps or cracks in walls or ceilings; and A_o (m^2), windows or cracks in facades.

Both exhaust and supply areas are known but leakages areas have to be estimated.

The smaller the leakage gaps are, the higher the gradient is. This is an important parameter because if the gradient is small enough, some fresh air could enter in the burning room helping the development of the fire.

Some dimensionless parameters are used to calculate the volume of air which would enter or leave the room according to the initial volume, V_{room}, so these parameters must be understood like "volume times":

$s_s = A_s / (A_s+A_e+A_i+A_o)$: Volume of smoke spreading in the incorrect way

$s_V = T_n / T_1 - T_n / T_2 \approx 1 - T_n / T_2$: Excess of fire volume versus the room volume

T_n, T_1 and T_2 are temperatures in Kelvin (K)

s_s could be obtained from the simulations. When we run a simulation we can obtain the flow of smoke which goes by the incorrect way, this idea is explained in the *chapter 8.1 Data Analyze. PFS limitations and Matlab program.*

The area of the leakages must be estimated. It strongly depends on the building techniques. Concrete prefabricated panels have quite high air tightness, the junctions are sealed with silicone and high quality can be obtained.

Some experiments have resulted in a flow of leakages of 0.4 $l/s \cdot m^2$ per square meter of envelope (walls, floor and ceiling) with a pressure difference of 50 Pa.

6.5. Rules of thumb for limit smoke spread case for supply and exhaust ventilation systems

Under normal conditions there is over pressure in the supply duct and under pressure in the exhaust duct to drive the flow in the correct way. As it has been said before, when a fire occurs the gas volume will increase while the pressure and the room volume will remain constant (1bar and V_{room}).

The excess of air will leave the room through any “exit” it finds; both desired ways like exhaust system or leakages and undesired ways like the supply system causing smoke spread to other dwellings.

Working with gauge pressures and assuming that the absolute value drop is equal both for supply and exhaust system, $p_s=-p_e$, the operating situation is:

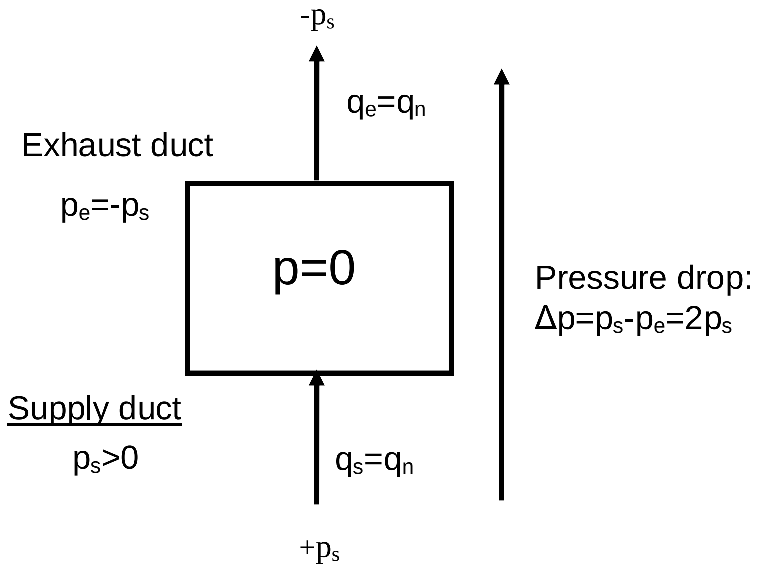


Figure 6 .4. Normal pressure disposition.

The pressure drop from the supply to the exhaust duct is p_s - $(-p_e) = 2p_s$. The pressure drops set in the main duct it is assumed to remain constant. If the excess of pressure is larger than P_s the supply air would be blocked because the pressure gradient would be zero.

When the flow inside the supply duct is blocked, $q_s=0$. The drop pressure between the room and the ducts is $\Delta p = p_{s,e}\,(q^2/q_n^2)$. In this situation the air which is exhausted is the flow from the fire q_f so:

$$\Delta p = p_e\,(q_f^2/q_n^2) + p_s\,(0/q_n^2) = 2p_e$$

$$q_f = \sqrt{2}\,q_n$$

Consequently, if the fire flow is √2 times the normal flow, q_n, the supply duct is blocked.

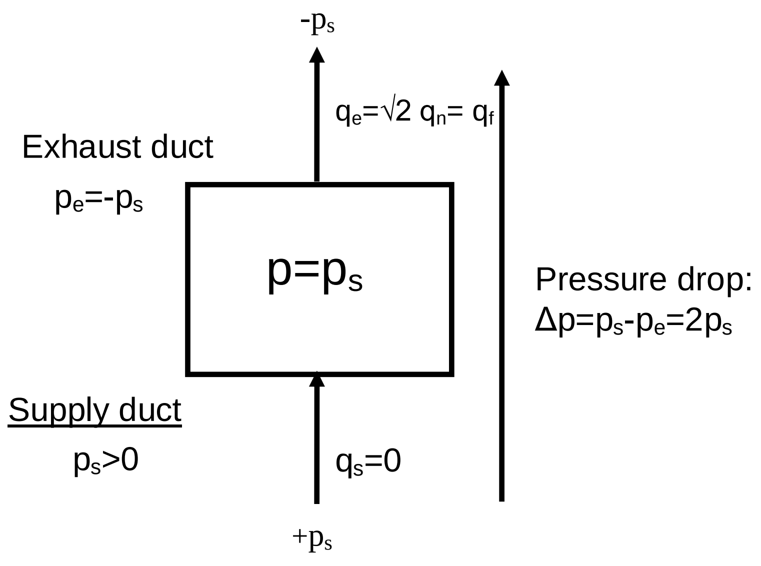


Figure 6.5. Pressure and flows in the limiting case to block the supply.

To illustrate this fact, a numerical calculation can be done:

Our dwelling must be supplied with q_n=40 l/s, which is the same 0.04m^3/s. The volume of the apartment is 250 m3 (99.7 m^2 x 2.5 m) approximately. Considering an interval of time of two minutes, 120 seconds, and the flow of the fire $\sqrt{2}q_n$ we can estimate which would be the minimum temperature which will block the supply system:

$$q = V\,(T_2 / T_1 - 1) / (t_2 - t_1)$$

$$T_2 = T_1\,(q\,(t_2 - t_1) / V + 1) = 300K\,(\sqrt{2}\cdot 0.04\ m^3/s \cdot 120\ s / 250\ m^3 + 1) = 308.15\ K$$

Just an increase of 8 Kelvin will cause the blockage of the flow inside the supply system. The predicted temperatures after 2 minutes for a dwelling either with a sofa or a bed burning are around 540 Kelvin. Consequently, we may accept that the blockage of the supply system will take place.

When this value is overcome smoke spread through the supply system is likely to occur. It is very important to predict it and take actions to avoid dangerous situations.

The flow of smoke which has been calculated is "the cold case". This means that the temperature of the smoke is equal to the environment air, 20 ºC. Obviously, the temperature of the smoke is going to be higher and the density of the smoke must be adjusted.

The drop of pressure between the supply and exhaust side is the same, $2p_n$, but in this case the pressure due to the fire flow is balanced:

$$\Delta p = (\rho/\rho_n) \cdot p_e \cdot (q_f^2/q_n^2)$$

$$\rho \rightarrow \textit{Smoke density at } T_{fire}$$

$$\rho_n \rightarrow \textit{Normal density } T_n$$

$$T_{fire} > T_n \rightarrow \rho < \rho_n$$

The density depends on the temperature (in Kelvin); the bigger the temperature is the lower the density, therefore:

$$\Delta p = (\rho/\rho_n) \cdot p_e \cdot (q_f^2/q_n^2) + P_s\,(0/q_n^2) = 2P_e$$

$$q_f = \sqrt{(\rho_n/\rho)} \cdot \sqrt{2}\,q_n > \sqrt{2}\,q_n$$

This means that the real flow of smoke needed to block the supply system, and the resulting smoke spread, is bigger than the flow calculated for "the cold case". Thus, the simple calculations done under the cold assumption are valid because they guarantee the safety of the system.

To show these results, both the cold case, 20 ºC, and a hot case with a temperature of 600 ºC has been tested. The fire has been placed in the top floor, but the results are the same in the different stories. The normal supply flow is 40 l/s so, for the cold case, the "limiting" flow should be $\sqrt{2} \cdot 40$ l/s ≈ 57 l/s:

Although the PFS programme has not been introduced yet, at this point it is useful to show the following figures in which the simulations corroborate the previous results. The flow entering the sixth floor has been set zero and the programme has been demanded to calculate the necessary flow of fire to achieve this target.

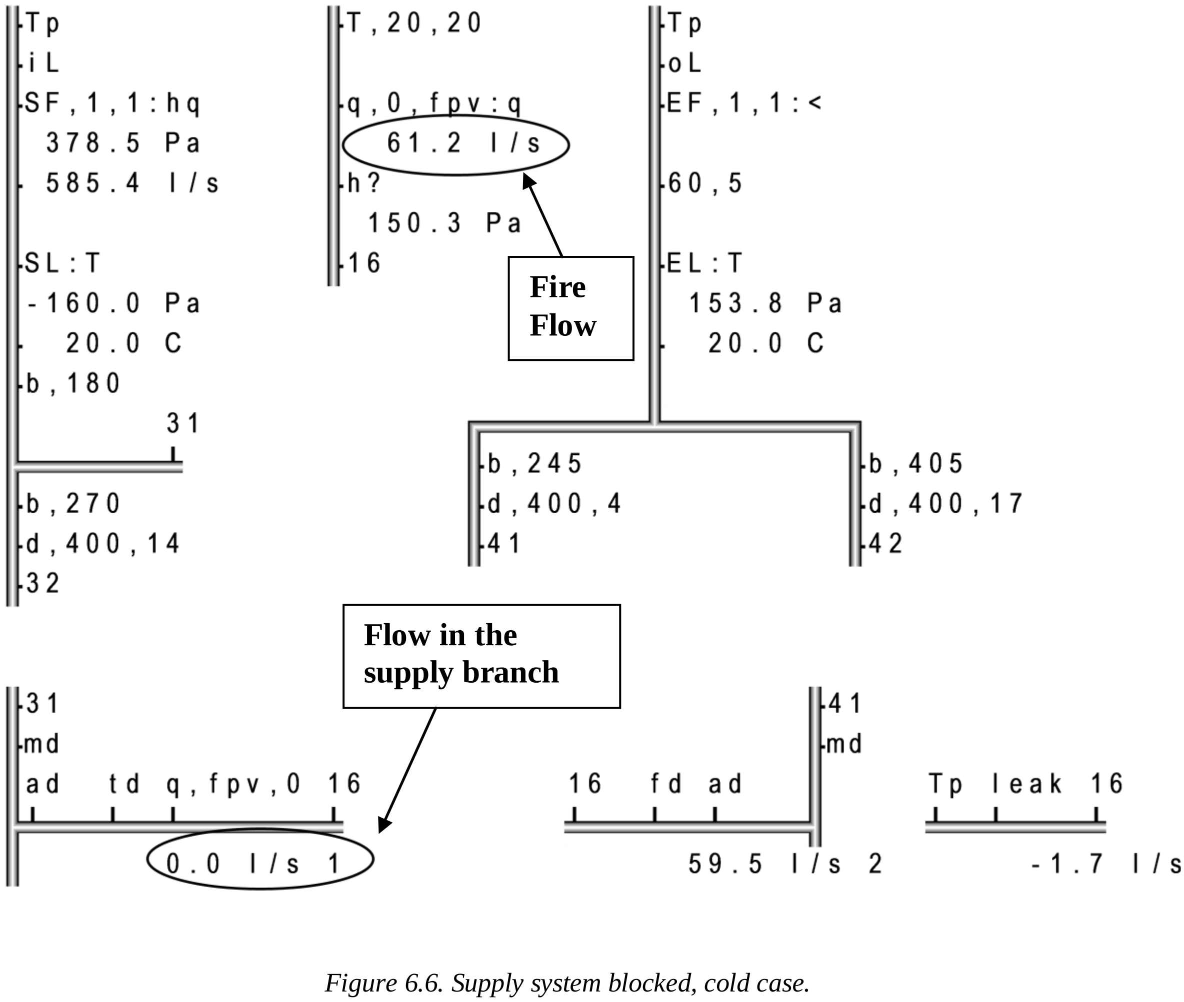


Figure 6.6. Supply system blocked, cold case.

The programme returns a value of 61.2 l/s, a figure very close to the predicted one and even a little bigger which guarantees the safety of the assumptions.

In the hot case, the temperature is three times higher (873/293 ≈ 3) so the density is three times lower and the expected flow should be $\sqrt{3} \cdot \sqrt{2} \cdot 40$ l/s ≈ 98 l/s

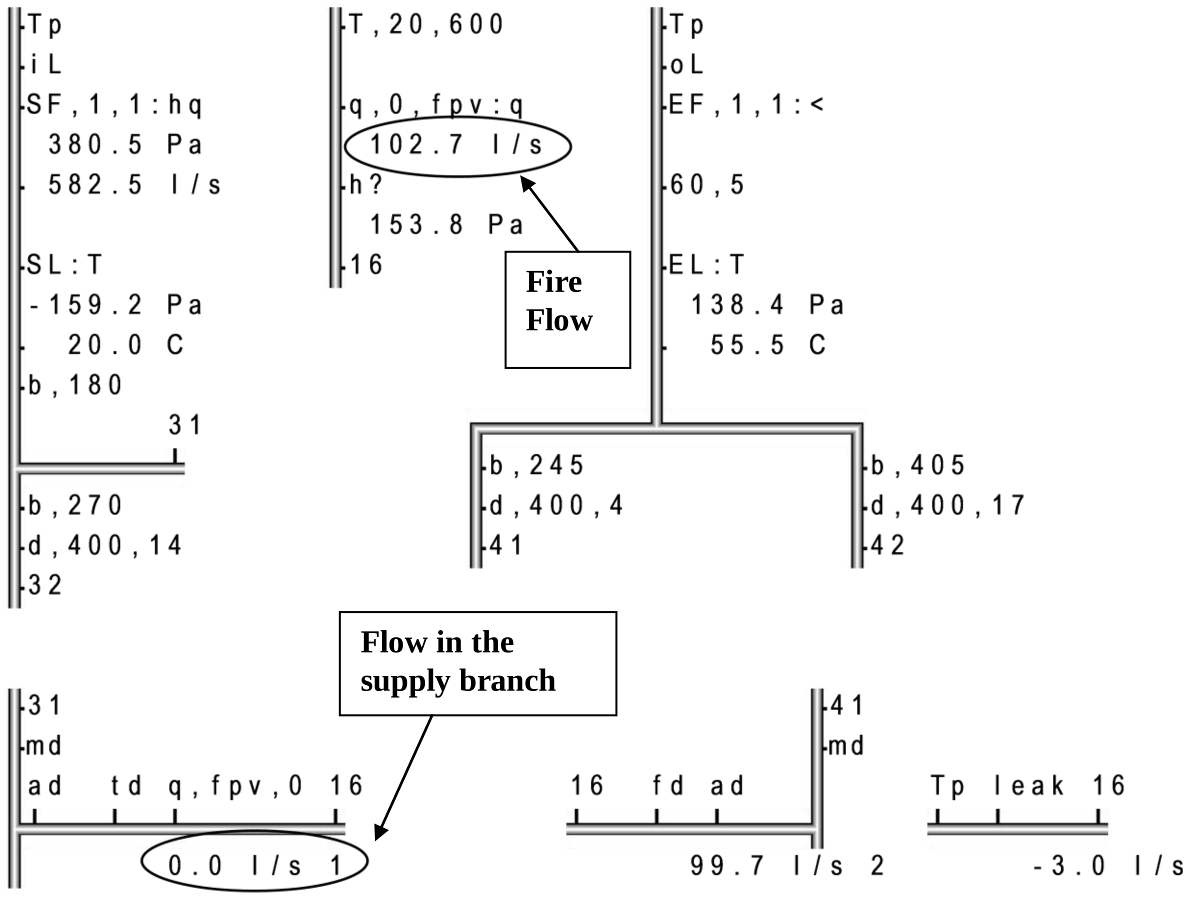


Figure 6.7. Supply system blocked, hot case.

In this simulation, the smoke flow needed to block the supply system is 102.7 l/s, in agreement with the predicted value.

6.6. Simple dilution calculation

The majority of the deceases caused by a fire are due to the smoke spread. It is very important to keep the toxic gases such as CO in safe levels during a certain time to guarantee the evacuation of the building. The room or flat in which the fire occurs is not the only space in trouble because as it has been said before, smoke spread is possible through the supply system or the internal leakages.

The main component of the fire gases is CO_2, but around 1% is CO. When dealing with CO, both the concentration of CO in the air and the exposure time are important. The

IDLH, immediately dangerous for life or health parameter, establish that a concentration of 10000 ppm in a minute is lethal, while for 30 minutes the value is 3000 ppm.

Therefore it is really important to estimate how much of the smoke is going to spread to the adjacent flats.

The volume of fire which has to be diluted can be calculated like:

$$u = (s_t \cdot s_V \cdot V_{room}) / n \cdot V_{room} = s_t \cdot s_V / n$$

$n \rightarrow$ *Number of rooms or volumes of the same size*

$s_t \rightarrow$ *Volume spread through the supply system*

$s_V \rightarrow$ *Excess of volume*

Both s_t and s_V have been defined before in the point *6.4, Rule of thumb of building leakage*.

The factor *"n"* plays a main role; the higher the number of flats to spread the smoke, the lower the concentration of the smoke. Under certain circumstances, the concentration of CO could be dangerous in an apartment, instead, if we open the system and we dilute the CO in more dwellings the dilution will be higher and the concentration of the gas will remain in a tolerable range.

The simulations gathered in the chapter 8, *Fire Smoke Simulations,* will provide very valuable information in order to design the system in a safe manner under any circumstance. Smoke spread is a very probable situation; therefore, it is vital to know how many litres will reach each apartment depending on the position of the fire in the building and the layout of the ventilation system we decide to build.

7. PFS program and model

The PFS program is a Lund University program written by Lars Jensen, professor of the Building Services Engineering Department.

This program allows sketching the layout of the system and calculates the flows and pressure drops along the ducts, bends or discharging losses.

The drawing of the system do not have to be realistic, it is just a sketch which makes the programme easier to understand and visualize for the user. The design factors like the length or diameter of the ducts have to be defined explicitly. If these values were wanted, the sketch will neither affect the results.

It is possible to work with mechanical devices such as fans or elements like dampers. The characteristics of them also have to be defined in advance.

The first command which should be written at the heading of the programme is *"begin"* as well as the programme should finish with *"end"* to define a PFS block.

The units we are working with ought to be set close to the heading also. The default units are m^3/s and Pa. For these simulations the flow has been defined in l/s and the pressure in Pascal, Pa, though this last parameter could have been skipped because it is the default one. The commands that should be written are:

flow l/s

pressure Pa

The number of decimals for these units can also be defined in this point writing the command "format" followed by the variable and the number of figures demanded.

Ex: The value of the flow will be given with two figures:

format q 2

The programme offers the possibility of changing the control variables which define the calculations. The bends, junctions, ducts, dimension changes and the density changes have been taken into consideration. The *"1"* means that this looses must be considered in the calculations. The normal looses for this variables are quadratics:

control bend=1 con=1 duct=1 dim=1 dencase=1

An especial command in the control line must be written, *trix*. The trix command is very important because it sets the working conditions and the simulations carry on. Depending on the value it takes, it is used to make adjustments in the system or to excite it. This command takes values from 0 to 3 in order to simulate the different situations of the model:

> *trix=0* The model has all the parameters defined and it only does a single calculation.
>
> *trix=1* The programme calculates the unknown parameters such as drops of pressure or flows. It is similar to the 0 position and we may define both like the working situations
>
> *trix=2* This position excites the system. Some values change and we can study how these changes affect the system behaviour.
>
> *trix=3* This position is similar to the previous one. It excites the system but the unknown values of the flow are taken from *trix 1*.

Usually we will work with *trix=1* and *trix=2* which means that the adjustments have been done under “the cold case”.

The main elements, commands and variables used for the models programming are listed below, they have been classified in different groups according to if they are used for a property of the system, a property of the flow, or devices and others.

This first group of elements it is used to define the properties of the system:

d → This element defines a duct or a pipe. The different characteristics of the element can be defined with this element. Following the “d” the first parameter is the diameter and the second one the length.

> *Ex:* *d,100,3*
>
> *A duct of 100 mm diameter and a length of 3 meters:*

b → This element defines a bend. This is a basic component in any system, and the programme takes into consideration the pressure drop due to its presence. The bends drawn in the sketch are taken into consideration also, so it is important to consider this point for the results.

Ex: b, 180

A bend of 180º

e → This element defines a pressure loss for example at the end of a duct when it discharges to an open volume or the outside.

Ex: e,1

A pressure loss with factor 1.

l → This element defines a linear drop of pressure. The ducts and devices cause drop of pressures. These drops must be known because they must be overcome by the flow to reach the different branches.

Ex: l, Δp, q

A drop of pressure of Δp (Pa) per q (l/s)

t → This element defines a quadratic drop of pressure. The ducts and devices cause drop of pressures. These drops must be known because they must be overcome by the flow to reach the different branches.

Ex: t, Δp, q

A drop of pressure of Δp (Pa) per q (l/s)

Sometimes the drop of pressure is unknown and it is wanted to be calculated. Using the symbol "?" this is achieved.

Ex: t?q

Calculates the drop of pressure per for the flow "q" (l/s)

Figure 7.1. t?9 calculates the drop of pressure in the duct when 9 l/s are crossing. In this case, it is 87.9 Pa.

o → This element switches between *trix=1* and *trix=2*. It works like a damper. Sometimes, especially in case of fire, some ducts must be closed to avoid the spread of fire. The default position of the damper is *closed.* Using “0” and “1” we can refuse this state and *open* the damper or agree to the state and keep it *closed* respectively. The state of the damper can be changed trough the different steps of the simulations.

Ex: *o,0,1*

The damper is usually opened but in further steps it will be closed

fan → This declaration line defines the properties of a fan. Three characteristics points must be provided to determinate its quadratic curve. The default operating speed can also be set. The programme adjusts the working point according to the demanded values of flow or pressure.

Ex: *fan FF* $P_1:q_1$ $P_2:q_2$ $P_3:q_3$ *nr*

Three characteristic points given by the height and the flow. The operating speed is given by “nr” however this is not a mandatory value.

The second group is used for the properties of the flow.

The programme works with a sign convention which regards like positive flows these which go to the right or downward and like negatives these ones to the left or upwards. This criterion also applies for the rest of variables such as drop pressure or temperature difference.

It is possible to define flows in the negative direction with the following symbol:

< → It sets that the flow or another variable goes in the negative direction, to the left or upwards.

Ex: T,40:<

This instruction sets that to the left or downwards the temperature of the flow is 40 ºC.

h → This element defines a pressure change in a point.

Ex: h,P

This instruction sets a pressure change of P (Pa)

q → This element defines the flow.

Ex: q,qs

This instruction sets a flow of qs (l/s) in a branch.

T → This element defines a temperature in a desire point. It is useful to define the temperature of the smoke we want to simulate.

Ex: T, C

This instruction sets a temperature of C degrees for the flow crossing the point.

v → This element defines the speed in the desire point.

Ex: *v, S*

This instruction sets a speed "S" for the flow in a desire point.

Usually these commands present more than one value after the definition. This means that the first values will be use in *trix=1,* like the normal operating value and the second one in *trix=2* to excite the system.

Ex: T, T_1, T_2

This instruction sets that in trix=1 the temperature will be T_1 *and in trix=2 it will be* T_2*. The programme understands the instruction like:*

trix=1 → T,T_1

trix=2 → T,T_2

Some other symbols are used to demand or set values

: → It has different functions. This element is used to demand printouts *(Ex.1)* or in combination with the command "<" to set flow properties upwards or to the right *(Ex.2)*. By itself defines a dummy element without pressure drop or change.

Ex.1: *t,10,50:q*

Writes the flow through this point.

:Tv

Writes the temperature and the velocity of the flow in this point.

Ex.2: *fan:<*

Sets that the fan moves the flow upwards or to the right. It is used for exhaust fans.

? → It asks the program to calculate a value.

Ex: *h?*

Calculates the change of pressure.

→ It sets a variable connection. During this work, it has been used to simulate the different positions of the fire.

Ex: *#,nr*

Changes the position of the connection according to the values of "nr"

w → It assigns a result number to a demanded value. If a certain value is wanted to be exported for further calculations, this instruction must be written following the desire command. It will assign a result value which can be read in the programme or exported.

Ex: *t?*Q_1*:qw*

The flow Q1 is required. The command assigns a number to it.

The desired results must be explicitly demanded in the heading of the programme using the command *result*.

Ex: *result 13*

result 14

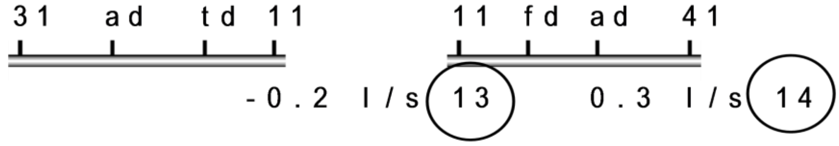


Figure 7.2. Results

The commands demand the results for points 13 and 14. In this case they are flows, the command <u>*td=t?40:qw*</u> *defines it.*

com → It defines a comment line. The instructions of the line are not taken into consideration for the programme.

Ex: com table 9 9 3 1

The instructions defined in the table are a comment.

fpv → It means *free parameter value*. The parameter defined this way can take any value. It is useful to calculate another value.

Ex: h,fpv

The pressure is unknown and it can take any value.

Figure 7.3. fpv

All this values and commands have been used in the model as the *figure 7.6* shows.
The model used in this thesis regards the dwelling like a whole. It is supposed that the rooms are inwardly connected. This assumption is based on the doors are not air tightness. It is quite realistic that the doors of the rooms usually are opened during the day.

To define which duct corresponds to each flat a number is used. Both the supply and exhaust ducts are named with the same number corresponding to the flat. The leakages to the outside are represented with a duct also named with the corresponding number and the properties of the environment at the other end.

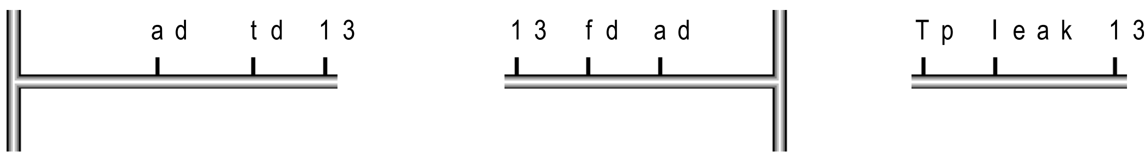


Figure 7.4. Third floor and its leakage.

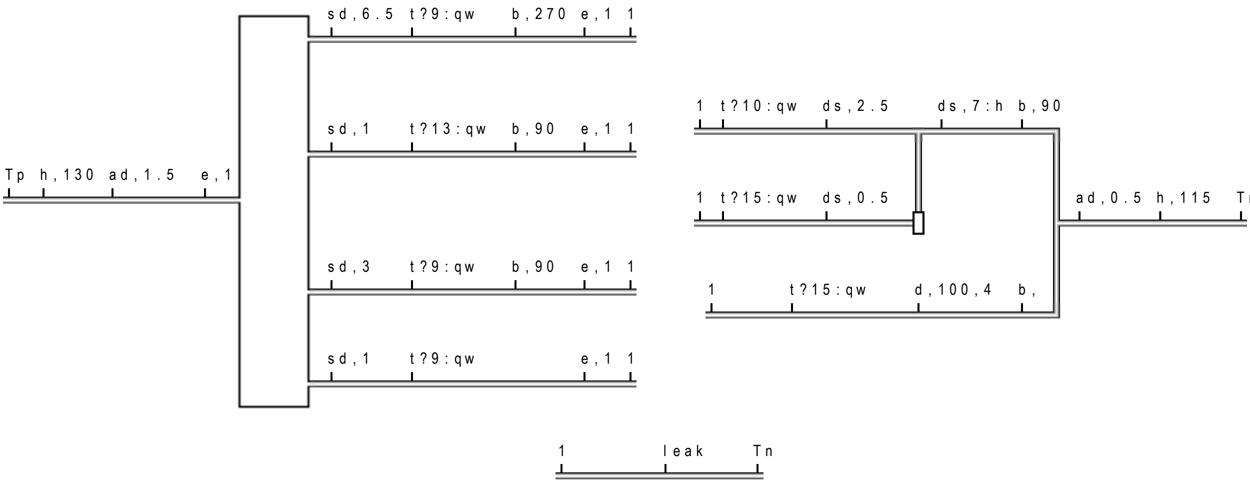
Each flat has two twin dwellings. The ducts are independent for each side, they are split in the air handle unit, and consequently we can consider that they are independent systems although the fans are shared.

Consequently, only the apartments of one side have been simulated. The other side has been considered like a single volume so the internal connections have not been taken into account. This assumption is explained and illustrated in the chapter 8 *Fire smoke simulations*.

```
begin
flow l/s
pressure Pa

format q 1
control duct=1 bend=1 con=1 dim=1 trix=1  dencase=1

set  ad=d,160    leak=t,50,40:q
set  sd=d,100    ds=d,125
set  Tp=T,20     Tn=T,20:<
```




```
com                                                              *
end
```

Figure 7.5. Sketch of the ventilation system inside the dwellings.

```
begin
flow l/s
pressure Pa
format q 1
control duct=1 bend=1 con=1 dim=1 trix=1  dencase=1
set  md=d,400,3    td=t?40:qw  SL=l,164,600:h iL=t,65,600
set  ad=d,160,1    fd=t?40:qw  EL=l,152,600:h oL=t,95,600
set  leak=t,50,1:q     tD=t?360:q
set  leaK=t,50,360:q   fD=t?360:q
set  60=d,600      Tp=T,20       Tn=T,20:<
set  non=o,0,1     noff=o,1,0

fan SF  500:0 470:417 160:834
fan EF  500:0 470:417 160:834
```

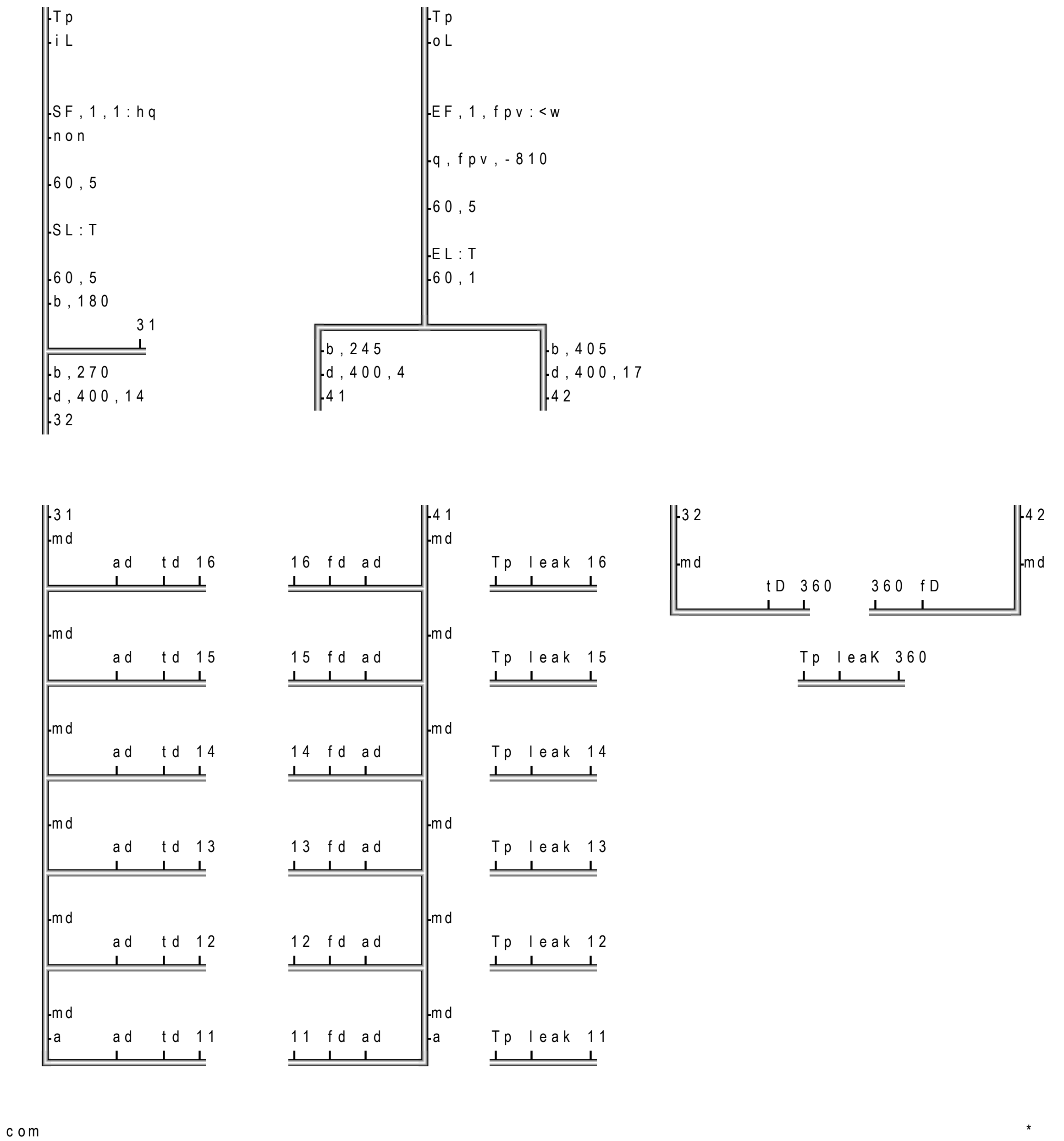


Figure 7.6. Sketch of the system. Normal operation model

Some variables are going to be used in several parts of the programme. They can be defined in advance at the begging of the programme with the command “*set”*.

The variables defined for this model are:

md → *md=d,400,3*

Main ducts both for supply and exhaust system. It has 400 mm of diameter and the length is 3 m, the height between stories.

ad → *sd=d,160,1*

Apartment duct. The diameter is 160 mm and the length considered is 1 m, the distance between the main duct and the distribution box. This duct has been use both for supply and exhaust ducts.

sd → sd=d,100

Internal supply duct. This variable has been used for the apartment simulations. The diameter is 100 mm and the length changes for each branch.

ds → *ds=d,125.*

Internal exhaust duct. This variable has been used for the apartment simulations. The diameter is 125 mm and the length changes for each branch.

noff → *noff=o,1,0*

It is a variable element that works like a damper. It switches during the normal operation it is closed and when the system is disturbed it becomes opened.

non → *non=o,0,1*

It is a variable element that works like a damper. It switches and during the normal operation it is opened and when the system is disturbed it becomes closed.

SF → *fan SF 500:0 470:417 160:834*

This declaration has been used to name the supply fan as *SF*. It is defined by three characteristic points.

EF → *fan EF 500:0 470:417 160:834*

This variable has been used to name the exhaust fan. It is defined by three characteristic points.

SL → *l,164,600*

It sets a linear drop of pressure of 164 Pa at 600 l/s in the devices (filters, heat exchanger, etc) of the AHU for the supply system. This data is provided by the manufacturer.

EL → *l,152,600*

It sets a linear drop of pressure of 152 Pa at 600 l/s in the devices (dampers, heat exchanger, etc) of the AHU for the supply system. This data is provided by the manufacturer.

iL → *t,65,600*

It sets a quadratic drop of pressure of 65 Pa at 600 l/s before the fan for the incoming air.

oL → *t,95,600*

It sets a quadratic drop of pressure of 95 Pa at 600 l/s after the fan for the outgoing air.

fd → *t?40*

It demands the drop of pressure in the exhaust ducts in the apartments for the normal flow 40 l/s.

td → *t?40*

It demands the drop of pressure in the supply ducts in the apartments for the normal flow 40 l/s.

fD → *t?240*

It demands the drop of pressure in the exhaust ducts for a whole side of the building for the total flow for six apartments, 240 l/s.

<u>tD</u> → *t?240*

It demands the drop of pressure in the supply ducts for a whole side of the building for the total flow for six apartments, 240 l/s.

<u>leak</u> → *t,50,40*

It sets a quadratic drop of pressure of 50 Pa at 40 l/s for the leakages in the apartments.

<u>leak</u> → *t,50,360*

It sets a quadratic drop of pressure of 50 Pa at 360 l/s for the leakages in a whole side of the buildings, it means six apartments.

<u>Tp</u> → *T,20*

It sets a positive temperature for the incoming air.

<u>Tn</u> → *T,20:<*

It sets a negative temperature for the out coming air.

It can be seen that not all the characteristics must be fixed when we set a variable. For example, the exhaust ducts inside the apartment have the same diameter but they have different length (2.5 or 7 meters); in this case, they can be defined as follows:

> *set   sd=d,100*
>
> *Then "sd,2.5" and "sd,7" defines the length for a punctual duct.*

Some different simulations have been carried out. Several layouts of the ventilation system, air flows or fire flows with different temperatures has been tested.

The different temperatures, flows and positions of the fire are defined by the following vectors:

> *Tf → It states the different temperatures simulated*
>
> *qf → It states the different smoke flows tested*
>
> *nr → It states the different positions of the fire.*

Certain values have been exported to further calculations. The required values are the fan speed (*result 1*), the pressure and the flow of the fire (*result 2 and result 3*) and the flows through the supply and exhaust system for the different simulations (*result 4-15*).

In the following pages these models and these vectors are shown and deeply explained, as well as the results and the conclusions obtained.

The result for basic model of the building is:

```
        begin
        flow l/s
        pressure Pa
        format q 1
        control duct=1 bend=1 con=1 dim=1 trix=1  dencase=1
        set  md=d,400,3   td=t?40:qw  SL=l,164,600:h iL=t,65,600
        set  ad=d,160,1   fd=t?40:qw  EL=l,152,600:h oL=t,95,600
        set  leak=t,50,1:q     tD=t?360:q
        set  leaK=t,50,360:q  fD=t?360:q
        set  60=d,600      Tp=T,20       Tn=T,20:<
        set  non=o,0,1     noff=o,1,0

radial  fan SF  500:0 470:417 160:834                rms= 0.000
radial  fan EF  500:0 470:417 160:834                rms= 0.000
```

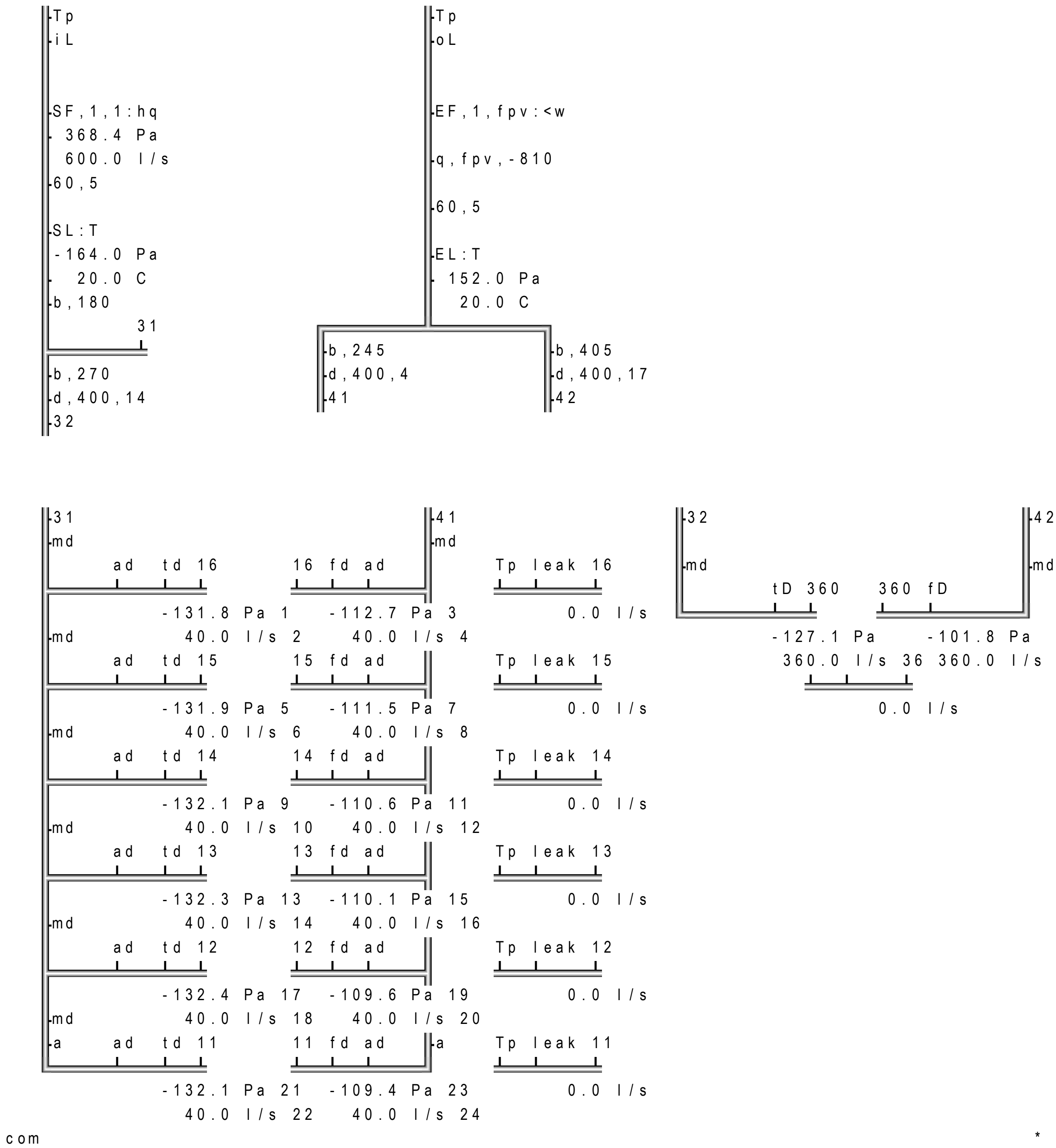


Figure 7.7. Result of the model. Flows and pressure drops

```
begin
flow l/s
pressure Pa
format q 1
control duct=1 bend=1 con=1 dim=1 trix=1  dencase=1
set  md=d,400,3   td=t?40:qw  SL=l,164,600:h iL=t,65,600
set  ad=d,160,1   fd=t?40:qw  EL=l,152,600:h oL=t,95,600
set  leak=t,50,1:q     tD=t?360:q
set  leaK=t,50,360:q   fD=t?360:q
set  60=d,600      Tp=T,20      Tn=T,20:<
set  non=o,0,1     noff=o,1,0

radial       fan SF  500:0 470:417 160:834                    rms= 0.000
radial       fan EF  500:0 470:417 160:834                    rms= 0.000
```

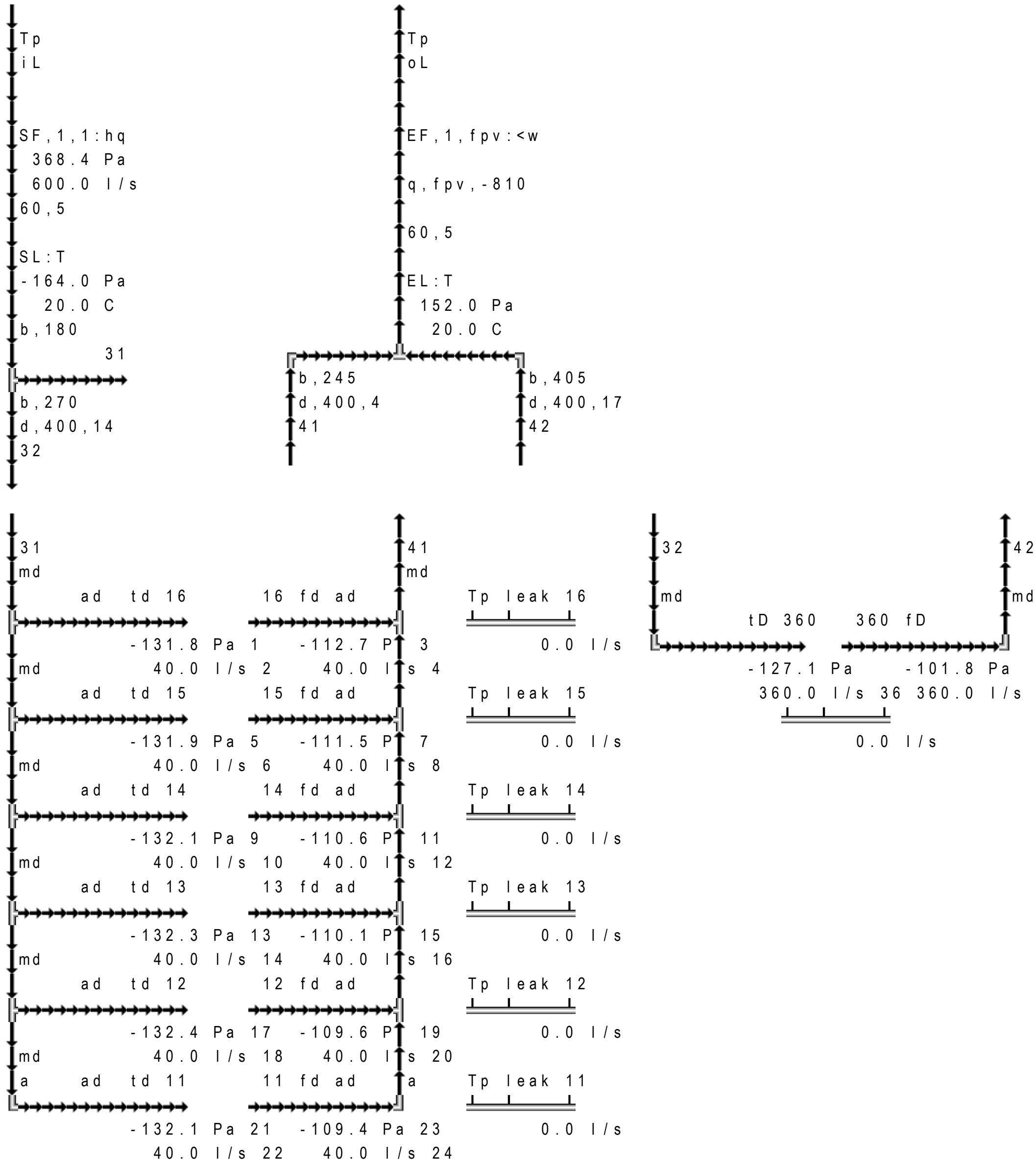


Figure 7.8. Result and flow pattern.

We can see the different flows and drop pressure trough the different branches of the system. Under normal working conditions each flat is supplied with 40 l/s and both the flows and the pressure drops are balanced between the supply and the exhaust side, there is not flow through the leakages.

8. Fire smoke spread simulations

The simulations have been carried out according to two boundary conditions: the maximum pressure of the gases must be below 5 kPa and the maximum temperature is 600 ºC

These boundary conditions are fixed by the characteristics of the dwelling envelope, especially the windows:

- The behavior of the glass cannot be guaranteed for values above 5 kPa so it is possible that glasses break down.
- Regarding the temperature, the envelope materials of the fire cell must be EI-60. This means that the resistance of the envelope is guaranteed during 60 minutes and 600 ºC.
- Cracks appear in the windows for temperatures in the range of 200-400 ºC.

Therefore, it is realistic to think that above these boundary values the appearance of other exits for smoke (broken windows, doors, etc) it is quite probable.

Consequently, the behavior of the ventilation system cannot be predicted for values out of these ranges and the study has been limited for these conditions.

Like it has been said in the chapter *7, PFS program and model*, an initial simulation has been done modelling both sides of the building with all their apartments. The results show that the smoke which gets to the other side of the building spreads uniformly along the apartments. Therefore, one side will be regarded like a single volume to simplify the computing process.

Also, this unique side considers the flow which reaches the common facilities of the building. The simulated side of the building is the most dangerous because the side connected to the bottom rooms has more volume to dilute the smoke.

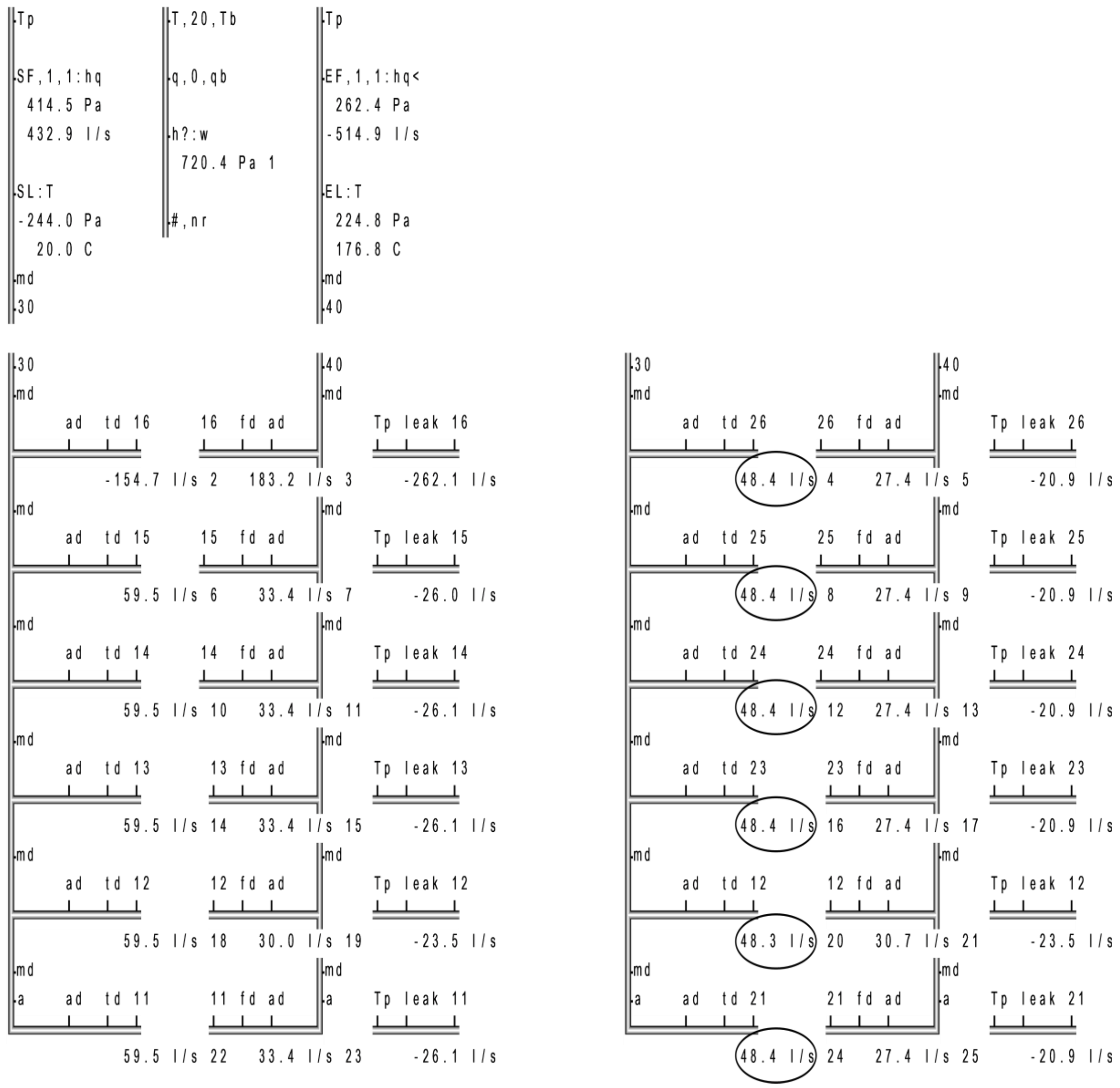


Figure 8.1. Complete model of the building. The flow reaching each dwelling is the same; all the apartments can be regarded like a single area.

The system must be safe whatever the circumstances are. A concentration of 10.000 ppm or 0.01 can cause the death in a minute; therefore this value has been set like reference because the fire can take place while people are sleeping without time to react.

The proportion of smoke reaching the most affected apartment must be lower than 0.01. This value is calculated as follows:

$$u = s_t \cdot s_V \cdot \frac{V_{burning\ cell}}{V_{receiving\ cell}} < 0.01$$

$$s_t = \frac{Flow\ reaching\ the\ flat\ (both\ from\ supply\ and\ exhaust\ system}{Fire\ flow}$$

$$s_V = \left(1 - \frac{T_{fire}}{T_{normal}}\right)$$

In this case both volumes are equal, so they are neglected in the calculations.

To simulate the fire flows in different flats and with different characteristics, an additional duct is used.

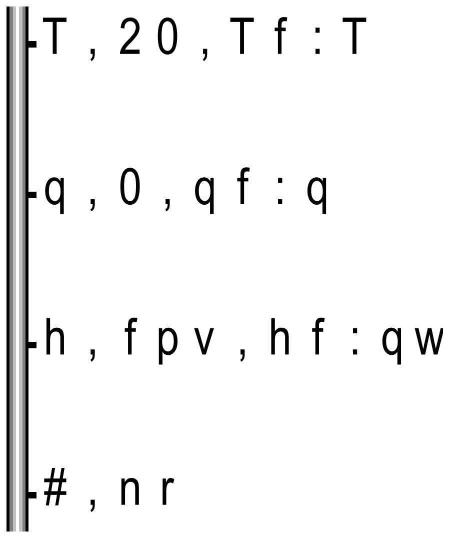


Figure 8.2. Fire duct.

This is a fictitious duct in which we can change the temperature, the flow and position of it.

The total number of simulations that PFS should carry out must be introduced manually using the command *table*. This number is the product of the dimensions of the vectors.

Four values have to be defined in the command "*table*"

table V_1 V_2 V_3 V_4

V_1 → The total number of simulations or combinations.

V_2 → The number of steps shown in a single line for each demanded result on the screen. The maximum number which can be shown in each line is twenty.

V_3 → The case shown in the sketch.

V_4 → Defines if the table of errors and observations is shown at the end. It can be 0, 1 or 2. If the value is equal to "0", a table with such lines as combinations and the observations of each one. If the value is "1", only a summarizing line is written. If the value is "2", no observations are written at the end.

We can define using the command *"program"* vectors which contain the different conditions we want to test.

Example:

program	*Tf*	*C*	*0*	*200 400 600*	*Different temperatures*
program	*qf*	*l/s*	*0*	*300 400 500 600*	*Different flows*
program	*nr*	*-*	*0*	*11 13 16*	*Different flats*

The first position of the vector defines the units we are working with, in this example, Celsius degrees for the temperature and l/s for the flow. Obviously, the position of the fire has not any unit and a "-" is written instead.

The second position is the number of decimals we want to work with. It has been set zero.

The following positions are occupied by the different values and configurations we want to try.

The end of the duct is reserved for the number of the flat in which we want to have the fire.

Some values are wanted to be read for the different simulations, they must be explicitly specified.

These required values are the fan speed (*result 1*), the pressure and the flow of the fire (*result 2 and result 3*) and the flows through the supply and exhaust system for the different simulations (*result 4-15*). The different results will be collected in the table and can be shown on the screen.

Finally all the data is exported to *txt file*. The command used is "*export*" followed by the name of the file where the results should be recorded.

Ex: *export convertedducttop.txt*

An example of the complete code written for the simulations in this Thesis is following. Through the different layouts, only the name of the file to extract the data changes:

```
    table 72 10 16 1
com table 9 9 1 1



    program nr    -    0    11 13 16
    program Tf    C    0    200 400 600
    program qf   l/s   0    300 400 500 600 700 800 900 1000
com program qf   l/s   0    fpv
    program hf    Pa   0    fpv
com program hf    Pa   0    5000

          result 1
          result 2
          result 3
          result 4

          result 5
          result 9
          result 13
          result 17
          result 21
          result 25

          result 6
          result 10
          result 14
          result 18
          result 22
          result 26

          result 7
          result 11
          result 15
          result 19
          result 23
          result 27

          result 8
          result 12
          result 16
          result 20
          result 24
          result 28
```

Figure 8.3. Simulation code.

A first simulation is carried out to determinate the maximum flow which fulfill the maximum pressure limit for the different temperatures. It results around 1100 l/s depending on the layout.

Consequently, the number of combinations will be 72 (8 flows, 3 temperatures, 3 positions: 8x3x3=72 combinations):

table *72 10 N_1 2*

Where N_1 is the desired case to be shown.

program qf l/s 0 300 400 500 600 700 800 900 1000

To set the flows which are wanted to be tested in each case.

Even though many combinations are simulated, the results obtained are similar for close configurations. It is useful to show some representative common cases in order to compare the results. If there is another critical situation out of these chosen cases, it will be remarked.

Then, once that it has been proved that the flows are below the maximum value, the different simulations are carried out.

The system is required to extract 810 l/s when a fire is detected. Looking for this purpose, the required value is set and the fan speed is a *free parameter value (fpv)*. The value reached for the speed is controlled in further steps because the characteristics of the fan allow an increase of the speed until a 30%:

```
-EF,1,fpv:<w

-q,fpv,-810
```

Figure 8.4. Required flow and free fan speed

8.1. Data analyze. PFS limitations and Matlab program

PFS program gives like results only the values and the signs of the flows but it does not show if the flow is smoke, fresh air or a mixture of both.

It is necessary to know the nature of the flow entering the dwellings in order to calculate the dilution. Otherwise, we may consider a flow of fresh air like smoke and the results will be false. With this purpose, a program has been written in Matlab.

The program use the data exported from PFS to make the calculations. The data has been collected from each dwelling both for supply and exhaust ducts and from intermediate points between floors in the main supply and exhaust ducts. Fire flow, temperature and position are also collected.

The program localizes the fire positions and checks the direction of the flow in the main supply duct backwards; this is the closest intermediate point in the main duct above the fire. Two situations may occur:

- The first possibility is that the flow in the main supply duct is positive. It means that there is some air coming from the supply fan, so some clean air is entering the system. Consequently, the floors above the burning room are not affected by the smoke, they only receive fresh air, and the floors below the burning room are receiving a mixture of smoke and fresh air.

  The composition of the “polluted” air that goes downwards is easy to calculate: The program divides the flow of smoke from the burning room by the addition of the smoke flow and the flow coming from the supply system.
  Then, all the flows entering the floors above the burning room are multiplied by the previously calculated composition obtaining the real amount of liters reaching each flat.

- The second possibility is that the flow is negative. It means that the smoke is spreading to the upper floors and the floors below the burning room are receiving only smoke.
  To decide the level reached by the smoke, the program checks the following points backwards in the main duct. If the value is negative it means that the smoke keeps going up; if the value is positive, the floor below the checked point is the last one affected by the fire and it receives the liters of smoke measured in the main duct below the floor.

This procedure is also used for the exhaust system. In this case, the program checks if the flow is going into or out of the apartment, and it only considers the cases in which the flow enters in the apartment.

The basic model has to be adapted for the different layouts depending on the particular characteristics of each one.

8.2. Normal operating system with fire. Case 00

The results for the original layout of the ventilation system are presented below. Both supply and exhaust fans are running and no safety measures have been taken.

The ducts have the dimensions previously listed, 600 mm for the ducts from the AHU, 400 mm for the main ducts and 160 mm for the apartment ducts.

The fans remain working when the fire occurs.

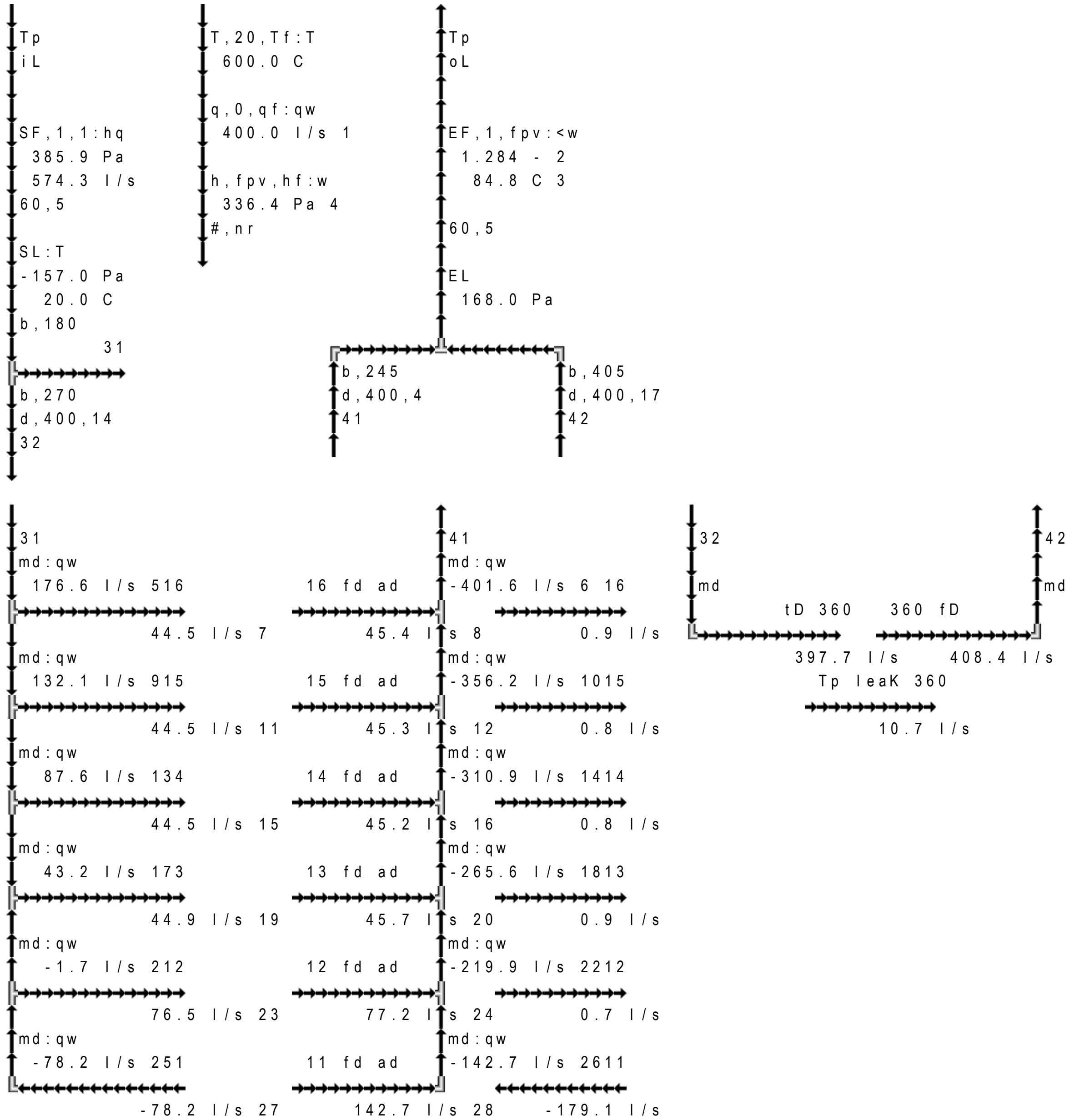


Figure 8.5. Operating system.

	Value	Fire floor	Fire flow (l/s)	Fire Temperature (ºC)	Fire pressure (Pa)
Limiting flow (l/s)	1146	6	-	200	5000
Maximum fire pressure reached (Pa)	3811	6	300	200	-
Maximum temperature in the fan reached (ºC)	198	1,3,6	1000	600	2082
Maximum percentage increase of fan speed	29%	6	300	600	199
Spread through the supply system	Yes				
Spread through the exhaust system	No				
Spread to the other side (maximum flow in l/s if the case is)	No			-	

	Smoke reaching the room (l/s)	Fire floor	Fire flow (l/s)	Fire Temperature (ºC)	Fire pressure (Pa)	Floor affected	s_t	s_V	Dilution Value
Maximum value of dilution	76	1	400	600	336	2	**0.19**	**0.66**	**0.13**

Table 8.1. Operating system results.

The first result that can be observed is that there is not any smoke spread through the exhaust system, once the gases enter in this system, they are directly lead to the outside.

The most dangerous situation in this layout is a fire in the first floor with a low pressure. If the fire occurs in the first floor, its only spread way is the supply duct. The overpressure created by the supply fan makes the smoke spread difficult and it may only reach one or two storeys.

When the fire occurs in the top floor or in and intermediate one, the supply system “helps” the smoke to spread through the different areas and the smoke reaching each flat is less.

The value of the dilution is above the limit; so this layout is not safe.

8.3. Normal operating layout. Supply fan shut down. Case 01

This layout switches off the supply system in case of fire; the smoke can only be extracted through the duct belonging to the exhaust system. The fan is shut down and there is a damper *"non"* placed to protect the supply fan.

The dimensions of the ducts are the standard: 400 mm for the main duct and 160 mm for the individual ones.

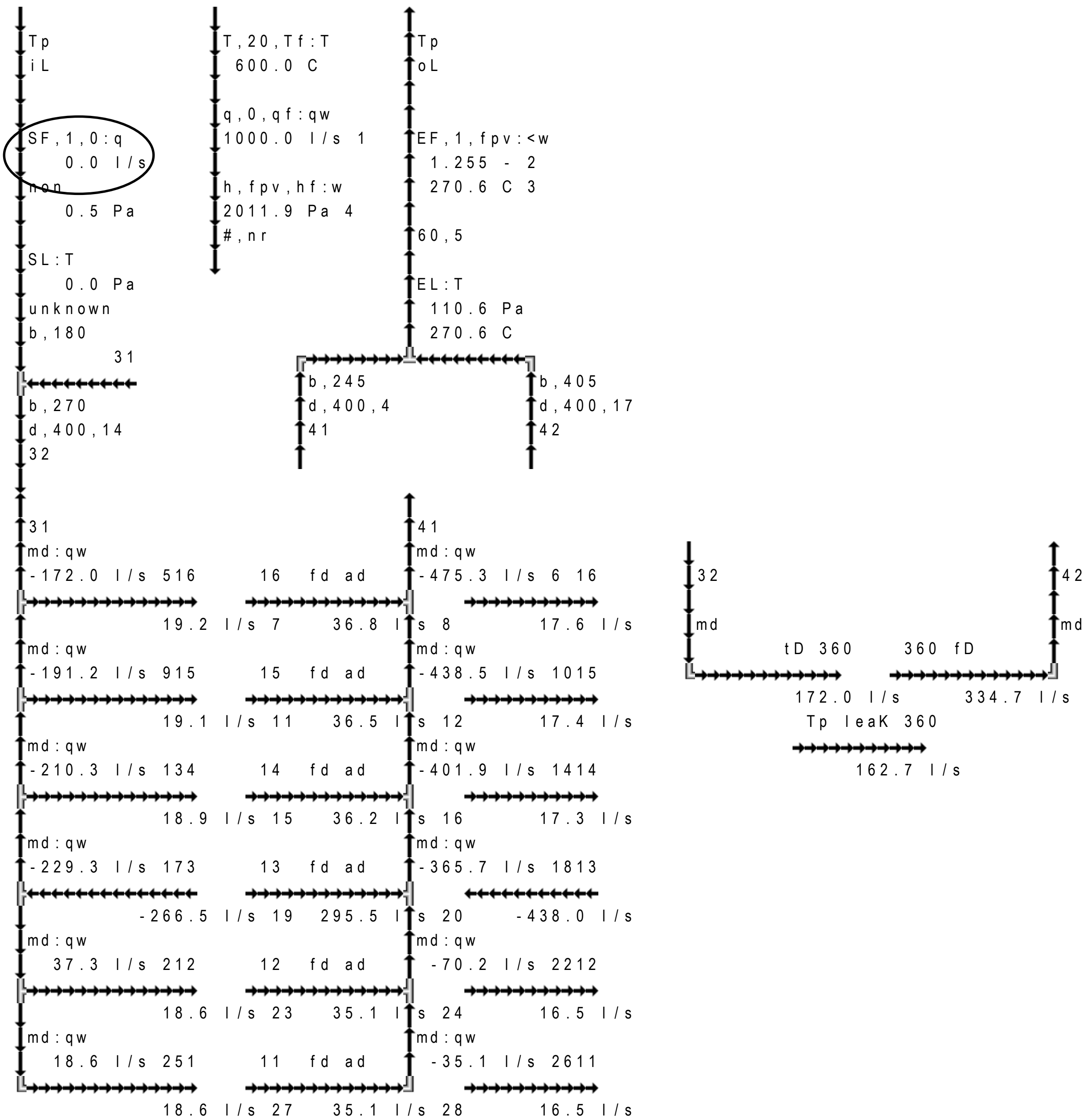


Figure 8.6. Normal operating system. Supply fan shut down

	Value	Fire floor	Fire flow (l/s)	Fire Temperature (ºC)	Fire pressure (Pa)
Limiting flow (l/s)	1153	6	-	200	5000
Maximum fire pressure reached (Pa)	3743	6	1000	200	-
Maximum temperature in the fan reached (ºC)	271	1	1000	600	2003
Maximum percentage increase of fan speed	34%	6	300	600	113
Spread through the supply system	Yes				
Spread through the exhaust system	No				
Spread to the other side (maximum flow in l/s if the case is)	No			-	

	Smoke reaching the room (l/s)	Fire floor	Fire flow (l/s)	Fire Temperature (ºC)	Fire pressure (Pa)	Floor affected	s_t	s_V	Dilution Value
Maximum value of dilution	19	3	1000	600	2012	6	**0.038**	**0.66**	**0.013**

Table 8.2. Normal operating system. Supply fan shut down. Results

Shutting down the supply system, the duct remains empty and it is an easy exit path for the smoke to reach different apartments. The overpressure and the density are the driving forces of this movement.

There is no smoke spread through the exhaust system; the smoke is lead to the outside.

It is not important where the fire takes place. The smoke spreads uniformly wherever the position is. The amount of liters spreading depends on the pressure, the higher this is, the more smoke liters spread.

The results show that there are many situations in which the speed of the exhaust fan is higher than the 30 % allowed. This scene is dangerous because the fan is overloaded and it may break down stopping the gas extraction.

8.4. Connection box. Case 02

This layout simulates all the apartments connected to a distribution box. There is not a main duct; each apartment is supplied directly from the box.

Consequently the ducts have a smaller diameter, 160 mm instead of 400 mm.

There are some discharging losses in the different boxes which have been taken into consideration in the model.

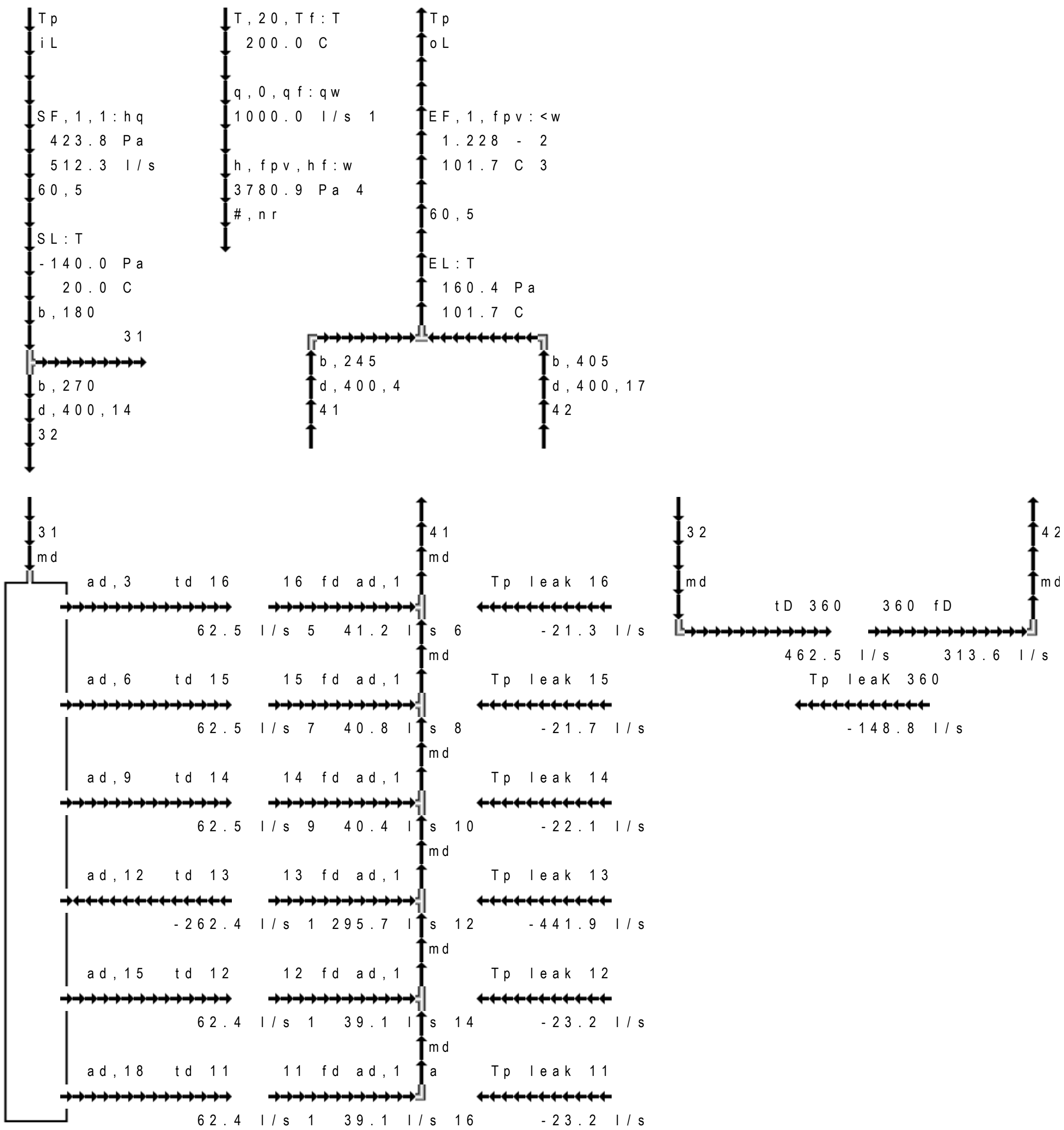


Figure 8.7. Connection box model

	Value	Fire floor	Fire flow (l/s)	Fire Temperature (ºC)	Fire pressure (Pa)
Limiting flow (l/s)	1146	6	-	200	-
Maximum fire pressure reached (Pa)	3740	6	1000	200	-
Maximum temperature in the fan reached (ºC)	200	1	1000	600	2055
Maximum percentage increase of fan speed	29%	6	300	600	199
Spread through the supply system	Yes				
Spread through the exhaust system	No				
Spread to the other side (maximum flow in l/s if the case is)	Yes			≈ 180 l/s	

	Smoke reaching the room (l/s)	Fire floor	Fire flow (l/s)	Fire Temperature (ºC)	Fire pressure (Pa)	Floor affected	s_t	s_V	Dilution Value
Maximum value of dilution	≈ 20	Any	Any	Any	Any	1,2,3,4,5	**-**	**-**	**0.012**

Table 8.3. Connection box results

In this model, the supply system is not switched off in case of fire. The fan keeps supplying air in the system.

As long as all the dwellings are connected to a common box, the smoke will spread uniformly, wherever the fire is, to all the apartments and all of them will be affected by the smoke in the same way increasing the available volume to dilute the smoke.

Simulations confirm this assumption; all the dwellings receive the same amount of air.

The previous idea has been considered to calculate the dilution. The maximum value of flow that reaches the connection box is 280 l/s. This situation takes places when the pressure is maximum.

The supply fan provides air according to the flow of the fire, the lower the fire flow the higher the supplied air.

8.5. Supply and exhaust connected at the bottom. Case 03

The basic layout is modified adding a duct at the bottom of the building. This duct connects the supply and the exhaust system.

The supply system works all time.

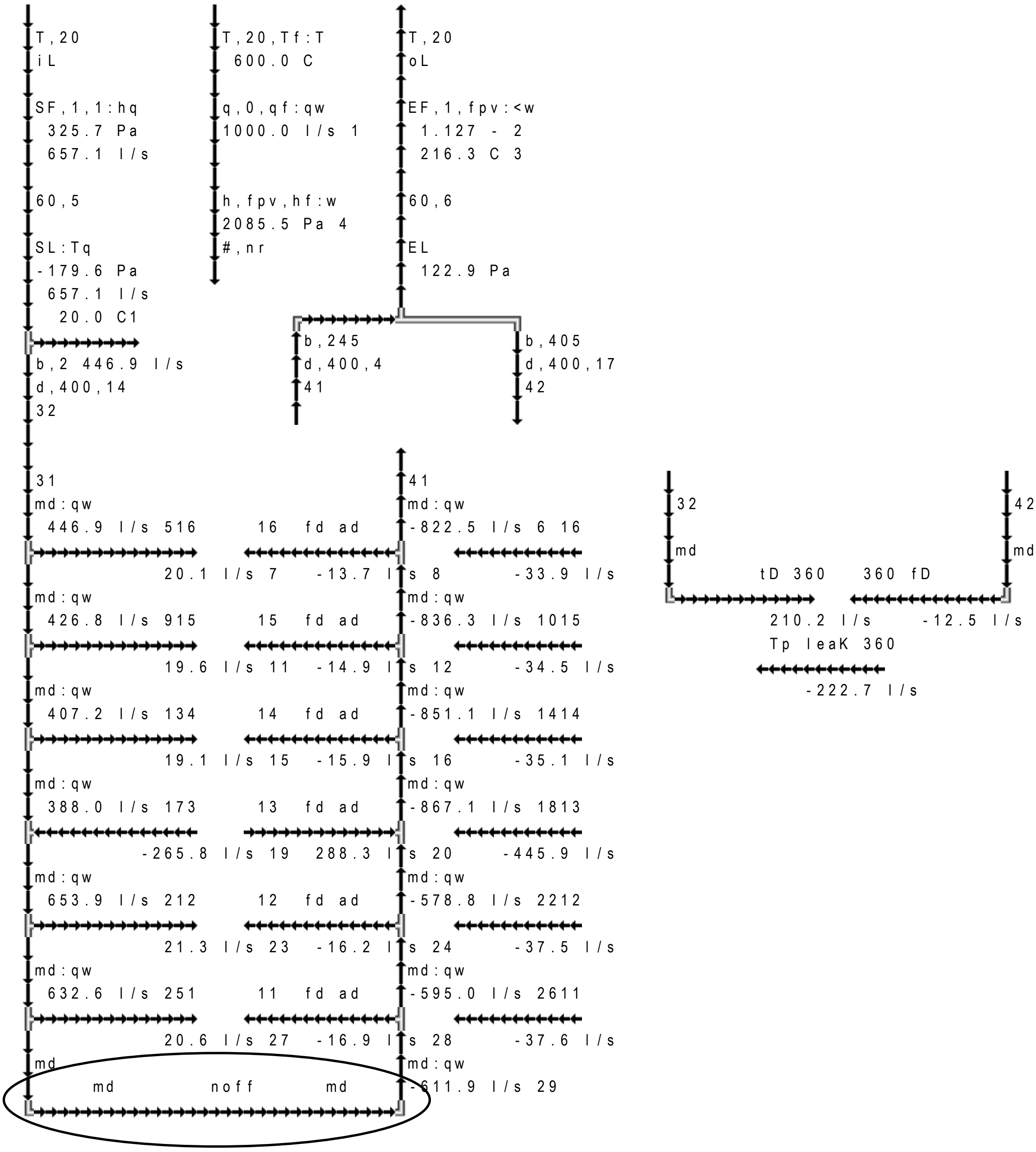


Figure 8.8. Supply and exhaust connected at the bottom model

	Value	Fire floor	Fire flow (l/s)	Fire Temperature (ºC)	Fire pressure (Pa)
Limiting flow (l/s)	1142	6	-	200	-
Maximum fire pressure reached (l/s)	3834	6	1000	200	-
Maximum temperature in the fan reached (ºC)	219	1	1000	600	2086
Maximum percentage increase of fan speed	17%	3	300	600	44
Spread through the supply system	Yes				
Spread through the exhaust system	Yes				
Spread to the other side (maximum flow in l/s if the case is)	Yes			17 l/s	

	Smoke reaching the room (l/s)	Fire floor	Fire flow (l/s)	Fire Temperature (ºC)	Fire pressure (Pa)	Floor affected	s_t	s_V	Dilution Value
Maximum value of dilution	15	3	1000	600	2085	1	**0.015**	**0.66**	**0.01**

Table 8.4. Supply and exhaust connected at the bottom results

The pressures achieved when the flow is maximum and the temperature is 200 ºC is very high, above 3800 Pa.

This layout presents some problems, the smoke spreads both through the supply and the exhaust system due to the higher pressures reached. The exhaust system cannot handle the over pressure and some flow escapes from this system.

Through the supply system, the smoke only affects the floors below the storey which contains the fire but through the exhaust system it may reaches any flat.

The smoke and the fresh air are mixed and this fact makes it difficult to determinate the composition of the gas entering the apartments. The data has been analyzed using Matlab to determinate the proportion of air and smoke that reaches the apartments.

8.6. Converted supply-exhaust system. Case 04

This is the original layout used in the Xchange project. There is a by-pass connecting the supply and the exhaust system inside the AHU.

In case of fire, the supplied system is shut down and the by-pass is opened. This way, the supply system is converted to exhaust system.

The dimensions of the ducts are the standard: 600 mm for the AHU ducts, 400 mm for the main duct and 160 mm for the individual ones.

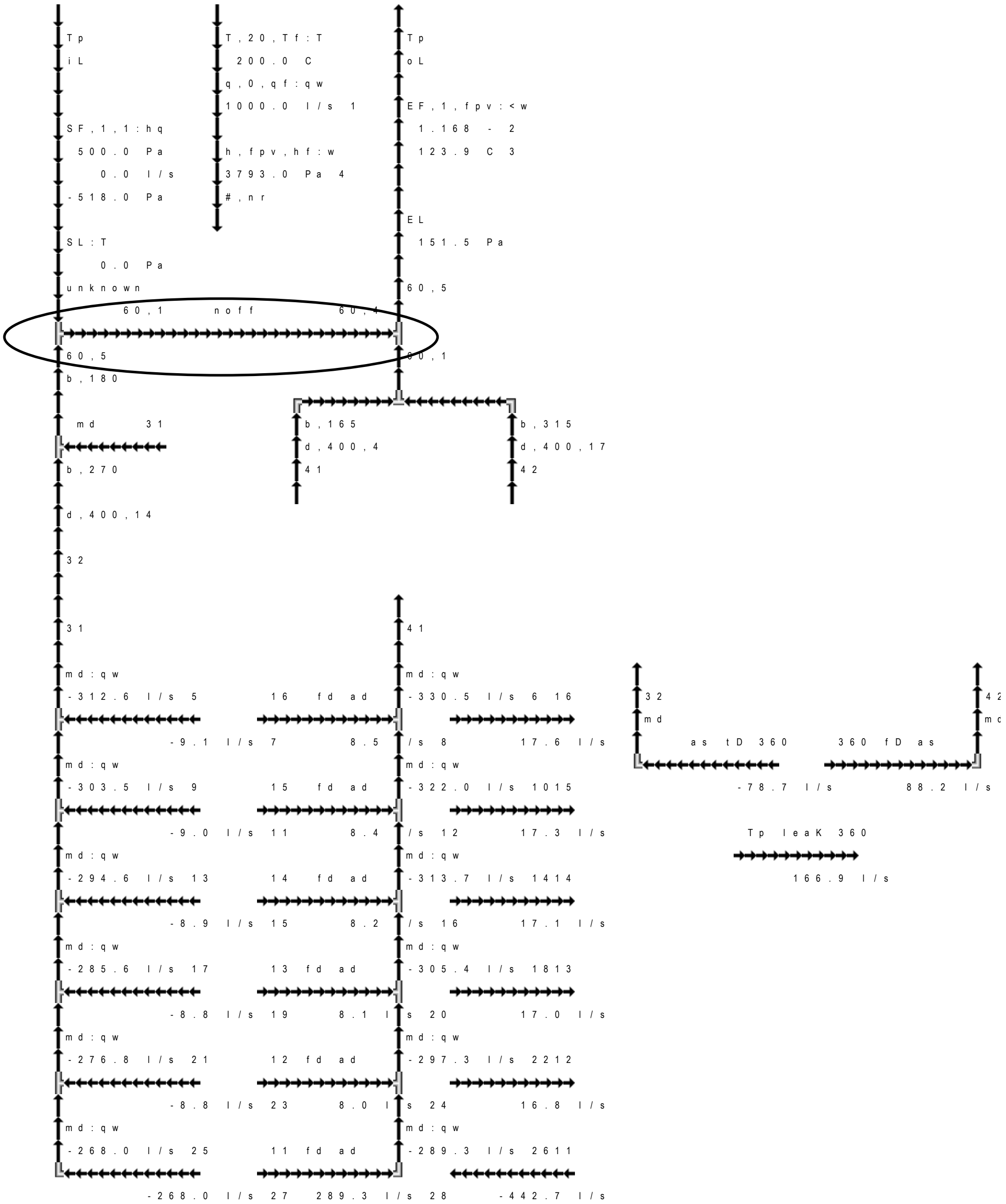


Figure 8.9. Converted supply-exhaust system

	Value	Fire floor	Fire flow (l/s)	Fire Temperature (ºC)	Fire pressure (Pa)
Limiting flow (l/s)	1146	6	-	200	5000
Maximum fire pressure reached (l/s)	3800	6	1000	200	-
Maximum temperature in the fan reached (ºC)	267	1	1000	600	2019
Maximum percentage increase of fan speed	24%	1,2,3	300	600	130
Spread through the supply system	No				
Spread through the exhaust system	No				
Spread to the other side (maximum flow in l/s if the case is)	No			-	

Table 8.5. Converted supply-exhaust system.

The results show that this layout is a good solution; there is not smoke spread under any circumstances.

The supply system performances like the exhaust one and the smoke does not reach other parts of the building.

The temperature of the exhaust gases could be a source of problem; for very large flows and high temperatures, 260 ºC have been registered at the entrance of the exhaust fan.

The speed of the fan has to be increased around a 24% to extract the smoke. The fan speed could be optimized; there is no air coming from the supply fan, and many liters leave the building through the façade. Some results show that there is an air flow from the outside which enters in the apartments through the leakages because the exhaust fan creates an under pressure inside the building. Reducing the fan speed the same results can be obtained and the fan reliability is guaranteed.

8.7. Open duct supply system. Case 05

There is a connection between the supply system and the outside. The smoke can be relived to the outside.

In case of fire, this duct is opened while the supply system keeps running.

The dimensions of the ducts are the standard: 400 mm for the main duct and 160 mm for the individual ones.

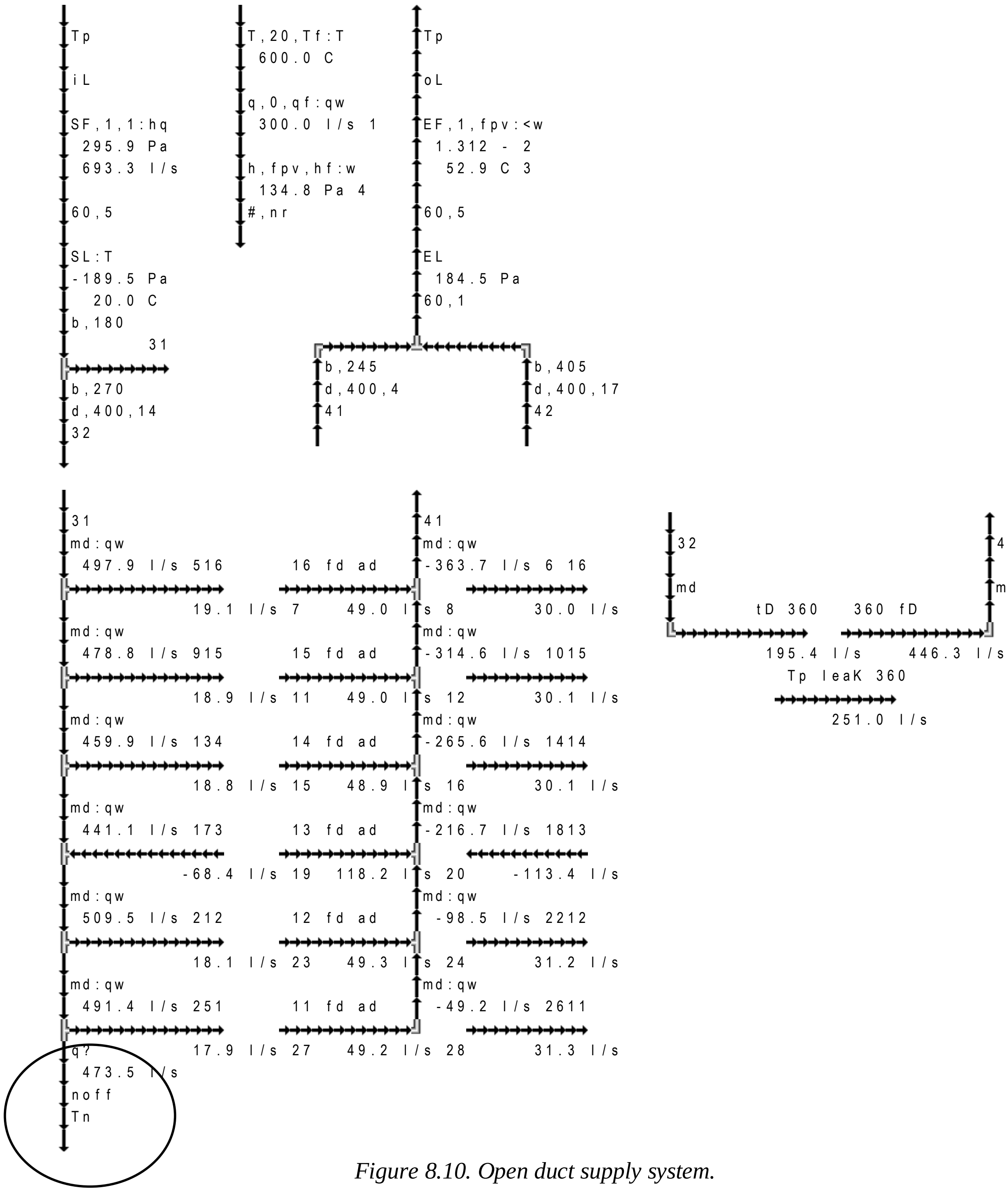


Figure 8.10. Open duct supply system.

	Value	Fire floor	Fire flow (l/s)	Fire Temperature (ºC)	Fire pressure (Pa)
Limiting flow (l/s)	1154	6	-	200	-
Maximum fire pressure reached (l/s)	3737	6	1000	200	-
Maximum temperature in the fan reached (ºC)	122	6	1000	600	2244
Maximum percentage increase of fan speed	31%	1,3,6	300	Any	150
Spread through the supply system	Yes				
Spread through the exhaust system	No				
Spread to the other side (maximum flow in l/s if the case is)	No			-	

Maximum value of dilution	Smoke reaching the room (l/s)	Fire floor	Fire flow (l/s)	Fire Temperature (ºC)	Fire pressure (Pa)	Floor affected	s_t	s_V	Dilution Value
	2.4	3	300	600	135	2	**0.008**	**0.66**	**0.005**

Table 8.6.Open supply system results

There is no smoke spread through the exhaust system.

Through the supply system the smoke spread is uniformed and it only reaches the floors below the flat where the fire is. Therefore it is a very advantageous design if the fire is placed in the first floor but some problems may appear when it is in the upper storeys.

The fresh air and the smoke are mixed, so the composition of the air entering the flats has been calculated using Matlab.

The layout is similar to the previous one but, in this case, the system is connected to the outside through the exhaust system.

In case of fire, this duct is opened while the supply system keeps running.

The dimensions of the ducts are the standard: 400 mm for the main duct and 160 mm for the individual ones.

8.8. Open duct exhaust system. Case 06

There is a connection between the exhaust system and the outside. Some fresh air can enter in the system in case of fire. This could be useful to reduce the temperature of the gases.

In case of fire, this duct is opened while the supply system keeps running.

The dimensions of the ducts are the standard: 400 mm for the main duct and 160 mm for the individual ones.

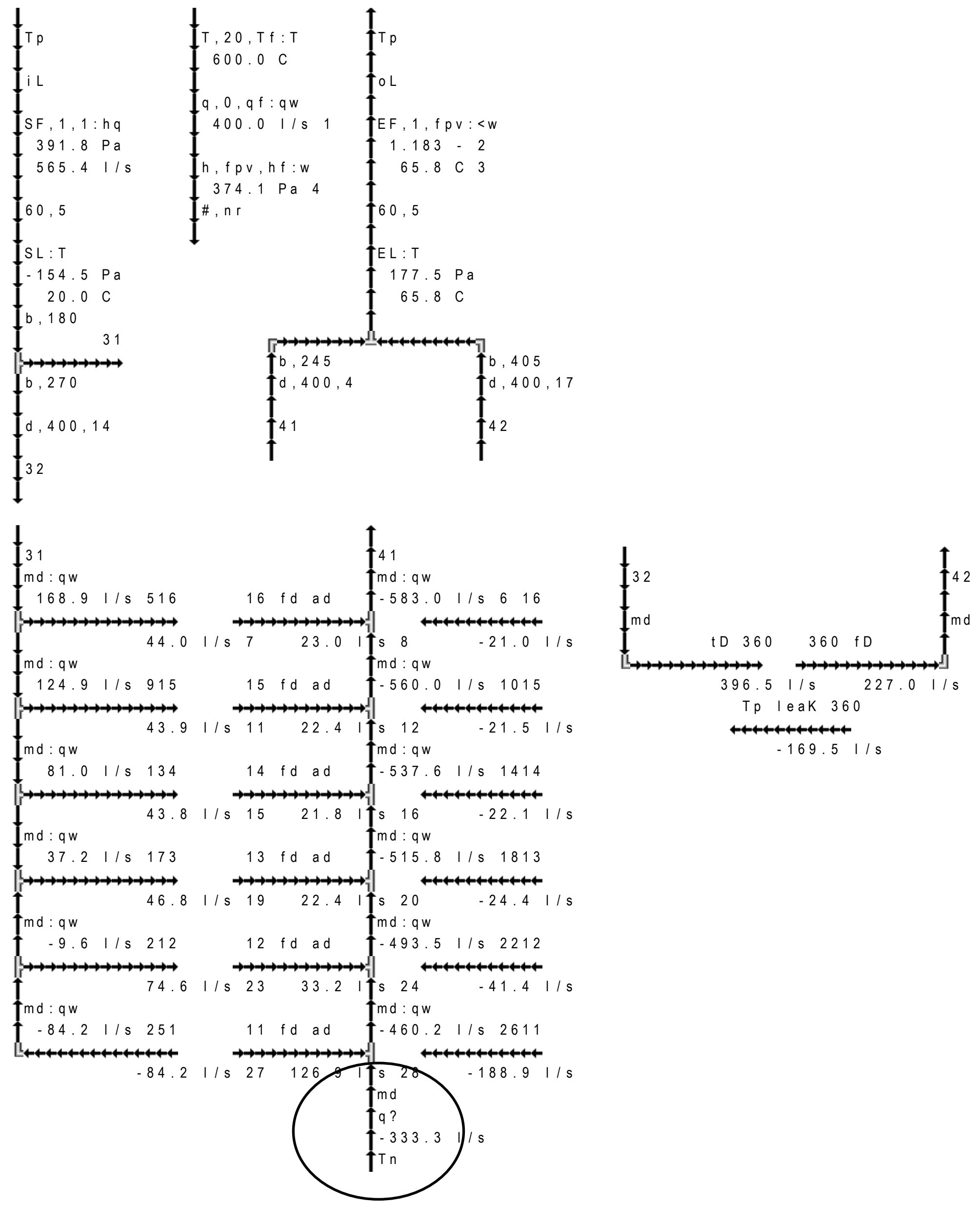


Figure 8.11. Open exhaust system.

	Value	Fire floor	Fire flow (l/s)	Fire Temperature (ºC)	Fire pressure (Pa)
Limiting flow (l/s)	1144	6	-	200	-
Maximum fire pressure reached (Pa)	3828	6	1000	200	-
Maximum temperature in the fan reached (ºC)	169	1	1000	600	2082
Maximum percentage increase of fan speed	18%	1,3,6	Any	Any	-
Spread through the supply system	Yes				
Spread through the exhaust system	No				
Spread to the other side (maximum flow if the case is)	No			-	

	Smoke reaching the room (l/s)	Fire floor	Fire flow (l/s)	Fire Temperature (ºC)	Fire pressure (Pa)	Floor affected	s_t	s_V	Dilution Value
Maximum value of dilution	74	1	400	600	374	2	**0.18**	**0.66**	**0.12**

Table 8.7. Open exhaust system

There is no smoke spread along the exhaust system.

The temperature of the exhaust gases and the fan speed are the lower.

The dilution requirements are not satisfied.

8.9. Results

The next table gathers all the results from the simulations:

Layout	***Smoke reaching the room (l/s)***	***Fire floor***	***Fire flow (l/s)***	***Fire Temperature (ºC)***	***Fire pressure (Pa)***	***Floor affected***	s_t	s_V	***Dilution Value***
Operating system. Case 00	76	1	400	600	336	2	**0.19**	**0.66**	**0.13**
Operating system. Supply shut down. Case 01	19	3	1000	600	2012	6	**0.038**	**0.66**	**0.013**
Connection box. Case 02	≈20	Any	Any	Any	Any	1,2,3,4,5	**-**	**-**	**0.012**
Supply and exhaust bottom connected. Case 03	15	3	1000	600	2085	1	**0.015**	**0.66**	**0.01**
Converted supply exhaust system. Case 04	**-**	**-**	**-**	**-**	**-**	**-**	**0**		**0**
Open duct supply system. Case 05	2.4	3	300	600	135	2	**0.008**	**0.66**	**0.005**
Open duct exhaust system. Case 06	74	1	400	600	374	2	**0.18**	**0.66**	**0.12**

Table 8.8 .Simulation results

The total number of simulations carried on in each layout is 72. The results shown are the worst situation that could take place. In these cases the value for dilution is the highest reached in the different configuration tested and therefore the most dangerous. Though the worst case may not be safe enough, there are many others situations in which the system satisfy the requirements.

The dilution value must be lower than 0.01 to regard the system like safe. With this criterion, only two systems are safe, the *"Converted supply-exhaust system. Case 04"* and *"Open duct supply system. Case 05"*

The *"Converted supply-exhaust system. Case 04"* is clearly the best; there is not any smoke spread. The system is absolutely safe; any apartment is affected by the fire because the exhaust system can handle all the smoke.

The *"Open duct supply system. Case 05"* is also a very good solution. Much smoke is relieved through this duct. The air coming from the supply fan helps to lead the smoke in this direction. It reduces the concentration of smoke in the air entering the apartments making the system very safe.

Some other systems like *"Normal operating system. Supply shut down. Case 01", "Connection box. Case 02"* and *"Supply and exhaust bottom connected. Case 03"* are very close to the limit, but they could be dangerous.

The system with the connection box, *Case 02*, can spread the smoke to a large volume reducing the gas fire concentration.

Both the operating system switching off the supply fan, *Case 01,* and the system with the duct connecting the supply and the exhaust system, *Case 03,* are close to be safe. The measures help to extract the air from the building. In the first case, the exhaust fan has to deal with a low volume of gases and it can almost exhaust the majority of the smoke. In the second configuration, the air can circulate along the system and it is easy for the gases to reach the outside.

The operating system by itself cannot handle the fire gases. Too many liters have to be extracted and the exhaust fan is not capable. The smoke cannot leave the building easily.

The layout with the exhaust system opened does neither agree the safety requirements. The pressure in the exhaust duct is almost the ambient one. The pressure difference between the supply and the exhaust side which should lead the smoke in the correct way to the exhaust system diminishes. Consequently, the exhaust side is not a preferential and the smoke leaves the apartment through both systems.

9. Discussions and conclusions

Some ideas, reflections and conclusions can be extracted from this thesis. The literature read to define the theoretical frame for smoke spread and its further implementation in the different models allows obtaining a general vision of the smoke spread problem.
The aim of this thesis is to provide some alternatives and solutions for the Xchange building analyzing the strong and weak points of each one. It is not a design guide for ventilation system and the results are restricted to the Xchange project. However, the bases of the design and some conclusions and suggestions gathered in this document could be suitable for other buildings.
The following conclusions regard different topics studied along the thesis such as, legislation, the relation between the fire characteristics and the building properties, smoke dilution and the possible solutions for the ventilation system.

9.1. Legislation

Latest statistics from USA or United Kingdom show that 400 and 265 people respectively died in fires due to the smoke. These deaths represent around a 75% of the total. The majority of the people killed in a fire were in a not burning room reached by the smoke.

The Fire Safety legislation is mainly focused on the structural reliability, the evacuation of the building or the necessary measures to guarantee the work of the emergency brigades.

Legislation only says about smoke spread that it “must be avoided”. This approach is too restrictive, the range of values within the toxic gases are not dangerous are known and a new approach could be possible. The systems are not more dangerous because of some smoke spreads along it if the system is correctly designed.

Some building codes, like the Spanish one, only requires a system capable of controlling the fire gases for certain constructions like tunnels or garages. Residential buildings do not have to satisfy any requirements about this issue.

The new Swedish legislation valid from autumn 2011 solves some of the previous problems. The dilution concept appears and the boundary limit for residential buildings is the one used along this work, 0.01. This limit rules for places in which people are expected to be sleeping like dwellings; if this is not the case, the boundary limit is 0.05, for example office buildings. The new law provides a reference value that will simplify the design process and guarantees its safety in case of fire.

9.2. PFS program and models

PFS is a very useful tool to analyze the smoke movement through the building. It offers the possibility of getting many parameters like pressure, flow, velocity or temperature in any place of the system.

Some problems had to be overcome during the simulations. The system solves the equations iterating and in a few simulations the residue error had to be increased. The default value is a 0.000001 and it was adjusted to 0.0001. The residue is small enough to guarantee that the results are correct.

The system should take into consideration the pressure losses in the connections of the ducts. This condition introduces problems in the iteration process because the pressure drop functions are not quite continuous and the program has some difficulties when the directions of the flows in the junctions change in the different steps. In some calculations it has been neglected. The drop of pressure in the junctions is not very big because the velocities of the flows are small; therefore the results are also valid.

The models have some limitations. The most important one affects the results obtained for the temperature in the exhaust fan. The temperature of the gases leaving the burning apartment in the program is the same than the fire gases. This is not real at all, because in the dwellings there is a huge volume of air at 20 ºC and much heat is lost through the envelope of the flat. Only if the supply grid is in the smoke layer the temperature will be the same than the fire. Therefore, the real temperature of the gases just before the exhaust fan must be lower than the predicted by the models.

9.3. Fire pressure and airtightness

Many results show that quite high pressures can be achieved during the fire progress. The different materials that are part of the building envelope have been studied and they should resist the pressures created during the fire event.

The pressures achieved during the fire are related to the building air tightness; the more airtight the building is the higher pressures are reached.

The temperature and the volume increase lead to a pressure increase. Simulations show that the exhaust system capacity to extract the fire gases is around the half if the building has no leakages. Also, high pressures, around 4 kPa, can occur for low fire flows creating dangerous situations.

The relative pressure difference between the supply and exhaust side with the fire cell becomes quite small and the exhaust duct is not a preferential path anymore. Then, the smoke spread through the supply system is more probable.

At these high pressures the hot gases collected on the ceiling can cross easily through the cracks to the upper floor.

The leakages opened to the outside of the building can be beneficial, the pressure is relieved and many smoke liters can leave the building through the façade, reducing the smoke liters that have to be extracted. However, uncontrolled fire gases leaving the building can spread the fire to upper floors.

Moreover, high pressure may cause problems to the inhabitants to leave the building. The door must open to the outside of the dwelling because above certain pressure it may be impossible to open it and the people may get trapped. If the doors open against the overpressure, the pressure difference should be limited to 80 Pa.

On the other hand, the hard weather requires a good isolation of the building. It is very important to reduce the leakages and modern constructions techniques are achieving this target.

Consequently, the building air tightness is a very important design factor. It influences the fan speed to achieve extracting the necessary smoke liters, the more airtight the building is, the bigger the load of the fan will be. Even, an extra fan could be needed if the speed is above the safe limits.

An alternative may be to install some devices to communicate the inside and the outside in order to relieve the pressure and lead hot gases out in a safe manner.

9.4. "Weak" fires

Along the simulations the most dangerous fires are those which could be described like "weak" fires. These fires have low pressure and low flow. They are not capable of spreading uniformly so the majority of the smoke only reaches the closest apartments.

This situation is especially dangerous if the fire takes place at the end of the supply duct, in this case the first floor, and the supply system is running because it makes even more difficult the gases spread. In this scenario, the previous floor connected to the main supply duct, the second floor in this project, receives a large amount of smoke while the other floors are almost not affected.

This fact is illustrated in the results, for the "*Normal operating system. Case 00"* a fire of 400 l/s at 600 ºC and a fire pressure around 300 Pa creates a very dangerous situation in the second floor.

If the fire reaches high pressures, it is capable of spreading to more floors reducing the relative amount received by each one. More dwellings are affected but in a less important way.

9.5. Smoke dilution

The results show, and it has been said before, that large flows are not more dangerous than small flows. The dilution value depends on two factors, s_t and s_V.

The s_V changes little in the simulations; the range of values is within 0.5 and 0.66.

Instead, s_t takes a wide range of values. It is remarkable that the same value of smoke reaching a flat gives different values depending on the fire flow. The same relative amount of smoke is more dangerous if it comes from a small volume of fire than if it comes from a large flow.

The reason is the duration of the fire. The duration of the fire and the smoke flow are inversely proportional. The relation is $q_f t = s_V V_{room}$. Like it has been said before s_V has a small range of variation, and anyway depends on the temperature. The volume of the room is constant. Therefore, $q_f \sim 1/t$, which means that a fire can release a large flow of smoke during a short period of time and vice versa.

To sum up the previous ideas, a small fire could be introducing smoke in an apartment for a long time producing a more dangerous situation than if the flow was larger.

9.6. Layout considerations

The ventilation system plays a very important role in case of fire. It must be designed in a proper manner and the smoke must be controlled in every moment. The ventilation system may be divided in two main parts, the ducts and the fans. The success of the layout depends on the correct design of both parts.

An important factor when designing a safety system is the reliability. One source of failure could be the fan. During the fire it must work above its normal operating speed. The fans are capable of facing this load but much time working under hard circumstances may lead to failure.

Results show that the higher the temperature is, the lower the fan speed must be to extract the desired volume. The power of the fan is proportional to the density and the flow raised to the cubic. In this case, the reduction of the fan speed is due to the decrease of the density.

Along the systems studied in this thesis, the exhaust flow is constant. The exhaust fan is always required to extract 810 l/s. Instead the density decreases with the temperature.
On the other hand, high temperatures may cause the failure by themselves.

The results are very clear about which the best layout is, a conversion system with the supply fan shut down, "*Converted supply exhaust system. Case 04",* agrees all the requirements; there is not smoke spread at all.

The systems in which the supply fan is switched off reduce the volume of air to be handled, but, the temperature of the exhaust gases is very high. This is for example the case of the "*Converted supply exhaust system. Case 04"*, the high temperature of the gases is its weakest point. There is any cold air from the outside entering the system and the air moving around the ventilation system is mainly fire gases.

In addition, it is cheap and easy to install. Only a duct is needed between both system and it does not require space inside the building. The connection can be done, like in the Xchange building in the AHU, on the roof where it does not take any spaces from the dwellings.

Those systems in which the supply is switched off, like "*Operating system. Supply shut down. Case 01"*, are also good solutions. The exhaust fan has to cope with a lower volume of air because there is no air coming from the supply fan, and this makes possible for the exhaust fan to extract the major part of the smoke.

It is important to emphasize the results from the supply duct open at the bottom, *Case 05*. It satisfies the dilution limits and the temperature in the fan is the lowest of the different layouts tested in this thesis. This is an important data to guarantee the fan durability.
This system is easy to build; only a duct is needed to connect the supply system with the outside. However, the gases must be driven carefully because its temperature will be high and if precautions are not taken some problems may occur.

A good solution could be to drive this duct to the roof again, like a chimney. Though, this solution demands the double space than the conversion system because a double duct is needed in the supply side.

Other layouts like the connection box can be theoretically a solution because it spreads the fire to all the apartments. In a big building like Xchange with 8 floors and 12 dwellings, there is a lot of volume available to dilute the smoke. If the building is smaller the dilutions may not be enough.

Although the figures show that in this case the value of the dilution is above the limit, connecting the whole building to the box the value will be lower than half.
This solution has to face some challenges, especially the space. The connection box is a big device. It must host 12 ducts of 160 mm and the main duct of 600 mm. The connection box can be placed in the roof where there is space available, although it should be very well isolated to guarantee the desired temperature for the supply air in normal operation. In addition, one duct is needed for each apartment which requires fairly space inside the building.

Another problem is that the connection box would have to be carefully designed because there is a risk of limited mixing inside the box. The box must be capable of mixing the smoke and the fresh air to dilute the smoke to the different apartments.

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11. Appendix:

Appendix A: Normal Operating System. Case 00

Appendix B: Normal Operating System. Supply System Shut Down. Case 01

Appendix C: Connection Box. Case 02

Appendix D: Supply and Exhaust Bottom Connected. Case 03

Appendix E: Converted Supply Exhaust System. Case 04

Appendix F: Open Duct Supply System. Case 05

Appendix G: Open Duct Exhaust System. Case 06

Appendix A : Normal Operating System. Case 00

Fire Floor	Fire Flow (l/s)	Fire Temperature (ºC)	Fire Pressure (Pa)	Sixth floor		Fifth floor		Fourth floor		Third floor		Second floor		First floor	
				Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution
1	300	200	342.44	0.000	0.000	0.000	0.000	0.000	0.000	1.973	0.002	56.488	0.070	0.000	0.000
3	300	200	343.13	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	29.226	0.036	29.229	0.036
6	300	200	344.25	0.000	0.000	11.755	0.014	11.759	0.015	11.759	0.015	11.759	0.015	11.759	0.015
1	300	400	246.41	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	49.433	0.092	0.000	0.000
3	300	400	247.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	24.501	0.046	24.502	0.046
6	300	400	248.73	0.000	0.000	9.853	0.018	9.854	0.018	9.854	0.018	9.854	0.018	9.854	0.018
1	300	600	197.29	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	39.384	0.086	0.000	0.000
3	300	600	198.89	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	19.383	0.043	19.385	0.043
6	300	600	199.53	0.000	0.000	7.801	0.017	7.801	0.017	7.801	0.017	7.801	0.017	7.802	0.017
1	600	200	1361.99	0.000	0.000	0.000	0.000	28.349	0.017	60.768	0.037	60.685	0.037	0.000	0.000
3	600	200	1365.97	0.000	0.000	0.000	0.000	28.551	0.018	0.000	0.000	60.686	0.037	60.693	0.037
6	600	200	1371.81	0.000	0.000	30.108	0.019	30.086	0.019	30.089	0.019	30.080	0.019	30.085	0.019
1	600	400	963.28	0.000	0.000	0.000	0.000	3.975	0.004	70.996	0.066	70.862	0.066	0.000	0.000
3	600	400	965.77	0.000	0.000	0.000	0.000	4.238	0.004	0.000	0.000	70.852	0.066	70.863	0.066
6	600	400	969.85	0.000	0.000	29.307	0.027	29.277	0.027	29.270	0.027	29.271	0.027	29.275	0.027
1	600	600	746.42	0.000	0.000	0.000	0.000	0.000	0.000	63.360	0.070	78.840	0.087	0.000	0.000
3	600	600	749.34	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	70.990	0.078	71.003	0.078
6	600	600	752.46	0.000	0.000	28.460	0.031	28.461	0.031	28.462	0.031	28.462	0.031	28.465	0.031
1	1000	200	3776.03	0.000	0.000	65.368	0.024	65.244	0.024	65.152	0.024	65.024	0.024	0.000	0.000
3	1000	200	3793.29	0.238	0.000	65.453	0.024	65.300	0.024	0.000	0.000	65.085	0.024	65.093	0.024
6	1000	200	3811.11	0.000	0.000	52.349	0.019	52.351	0.019	52.353	0.019	52.353	0.019	52.359	0.019
1	1000	400	2664.89	0.000	0.000	32.306	0.018	75.527	0.042	75.391	0.042	75.264	0.042	0.000	0.000
3	1000	400	2676.22	0.000	0.000	32.668	0.018	75.564	0.042	0.000	0.000	75.294	0.042	75.306	0.042
6	1000	400	2690.88	0.000	0.000	51.828	0.029	51.829	0.029	51.886	0.029	51.816	0.029	51.826	0.029
1	1000	600	2063.02	0.000	0.000	3.474	0.002	84.391	0.056	84.243	0.055	84.109	0.055	0.000	0.000
3	1000	600	2071.30	0.000	0.000	3.842	0.003	84.424	0.056	0.000	0.000	84.128	0.055	84.145	0.055
6	1000	600	2082.26	0.000	0.000	51.383	0.034	51.385	0.034	51.386	0.034	51.387	0.034	51.394	0.034

Appendix B : Normal Operating System. Supply System Shut Down. Case 01

Fire Floor	Fire Flow (l/s)	Fire Temperature (ºC)	Fire Pressure (Pa)	Sixth floor		Fifth floor		Fourth floor		Third floor		Second floor		First floor	
				Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution
1	300	200	258.78	5.551	0.007	5.492	0.007	5.442	0.007	5.406	0.007	5.413	0.007	0.000	0.000
3	300	200	259.41	5.561	0.007	5.503	0.007	5.453	0.007	0.000	0.000	5.368	0.007	5.370	0.007
6	300	200	260.48	0.000	0.000	5.441	0.007	5.442	0.007	5.442	0.007	5.442	0.007	5.445	0.007
1	300	400	163.15	5.560	0.010	5.499	0.010	5.447	0.010	5.413	0.010	5.430	0.010	0.000	0.000
3	300	400	163.61	5.577	0.010	5.517	0.010	5.466	0.010	0.000	0.000	5.342	0.010	5.345	0.010
6	300	400	164.27	0.000	0.000	5.407	0.010	5.408	0.010	5.409	0.010	5.409	0.010	5.412	0.010
1	300	600	112.63	5.578	0.012	5.513	0.012	5.458	0.012	5.423	0.012	5.445	0.012	0.000	0.000
3	300	600	113.00	5.601	0.012	5.537	0.012	5.483	0.012	0.000	0.000	5.322	0.012	5.325	0.012
6	300	600	113.43	0.000	0.000	5.384	0.012	5.385	0.012	5.385	0.012	5.386	0.012	5.389	0.012
1	600	200	1291.23	11.365	0.007	11.231	0.007	11.111	0.007	11.012	0.007	10.955	0.007	0.000	0.000
3	600	200	1295.63	11.382	0.007	11.250	0.007	11.131	0.007	0.000	0.000	10.963	0.007	10.962	0.007
6	600	200	1300.41	0.000	0.000	11.135	0.007	11.135	0.007	11.135	0.007	11.135	0.007	11.133	0.007
1	600	400	893.50	11.371	0.011	11.230	0.010	11.105	0.010	11.003	0.010	10.950	0.010	0.000	0.000
3	600	400	896.59	11.399	0.011	11.260	0.010	11.136	0.010	0.000	0.000	10.890	0.010	10.890	0.010
6	600	400	899.76	0.000	0.000	11.071	0.010	11.070	0.010	11.070	0.010	11.070	0.010	11.069	0.010
1	600	600	678.29	11.375	0.012	11.229	0.012	11.099	0.012	10.994	0.012	10.945	0.012	0.000	0.000
3	600	600	680.67	11.413	0.013	11.269	0.012	11.141	0.012	0.000	0.000	10.827	0.012	10.826	0.012
6	600	600	682.97	0.000	0.000	11.013	0.012	11.013	0.012	11.013	0.012	11.013	0.012	11.013	0.012
1	1000	200	3712.39	19.180	0.007	19.048	0.007	18.917	0.007	18.796	0.007	18.696	0.007	0.000	0.000
3	1000	200	3728.71	19.194	0.007	19.061	0.007	18.930	0.007	0.000	0.000	18.857	0.007	18.853	0.007
6	1000	200	3743.89	0.000	0.000	18.979	0.007	18.978	0.007	18.977	0.007	18.977	0.007	18.973	0.007
1	1000	400	2603.76	19.189	0.011	19.044	0.011	18.901	0.011	18.769	0.010	18.662	0.010	0.000	0.000
3	1000	400	2615.21	19.218	0.011	19.073	0.011	18.932	0.011	0.000	0.000	18.739	0.010	18.735	0.010
6	1000	400	2625.63	0.000	0.000	18.897	0.011	18.896	0.011	18.895	0.011	18.895	0.011	18.891	0.011
1	1000	600	2003.12	19.201	0.013	19.046	0.013	18.894	0.012	18.754	0.012	18.642	0.012	0.000	0.000
3	1000	600	2011.91	19.243	0.013	19.090	0.013	18.940	0.012	0.000	0.000	18.640	0.012	18.636	0.012
6	1000	600	2019.79	0.000	0.000	18.827	0.012	18.826	0.012	18.826	0.012	18.825	0.012	18.822	0.012

Appendix C : Connection Box. Case 02

Fire Floor	Fire Flow (l/s)	Fire Temperature (ºC)	Fire Pressure (Pa)	Sixth floor		Fifth floor		Fourth floor		Third floor		Second floor		First floor	
				Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution
1	300	200	342.296	4	0.005	4	0.005	4	0.005	4	0.005	4	0.005	0	0.000
3	300	200	342.893	4	0.005	4	0.005	4	0.005	0	0.000	4	0.005	4	0.005
6	300	200	344.458	0	0.000	4	0.005	4	0.005	4	0.005	4	0.005	4	0.005
1	300	400	247.605	3	0.007	3	0.007	3	0.007	3	0.007	3	0.007	0	0.000
3	300	400	248.025	3	0.007	3	0.007	3	0.007	0	0.000	3	0.007	3	0.007
6	300	400	248.985	0	0.000	4	0.007	4	0.007	4	0.007	4	0.007	4	0.007
1	300	600	198.867	3	0.006	3	0.006	3	0.006	3	0.006	3	0.006	0	0.000
3	300	600	199.189	3	0.006	3	0.006	3	0.006	0	0.000	3	0.006	3	0.012
6	300	600	199.816	0	0.000	3	0.006	3	0.006	3	0.006	3	0.006	3	0.012
1	600	200	1358.077	11	0.007	11	0.007	11	0.007	11	0.007	11	0.007	0	0.000
3	600	200	1362.87	11	0.007	11	0.007	11	0.007	0	0.000	11	0.007	11	0.007
6	600	200	1370.85	0	0.000	11	0.007	11	0.007	11	0.007	11	0.007	11	0.007
1	600	400	960.694	10	0.011	10	0.010	10	0.010	10	0.010	10	0.010	0	0.000
3	600	400	963.993	10	0.011	10	0.010	10	0.010	0	0.000	10	0.010	10	0.010
6	600	400	969.422	0	0.000	10	0.010	10	0.010	10	0.010	10	0.010	10	0.010
1	600	600	745.756	10	0.012	10	0.012	10	0.012	10	0.012	10	0.012	0	0.000
3	600	600	748.273	10	0.013	10	0.012	10	0.012	0	0.000	10	0.012	10	0.012
6	600	600	752.306	0	0.000	10	0.012	10	0.012	10	0.012	10	0.012	10	0.012
1	1000	200	3760.975	19	0.007	19	0.007	19	0.007	19	0.007	19	0.007	0	0.000
3	1000	200	3780.857	19	0.007	19	0.007	19	0.007	0	0.000	19	0.007	19	0.007
6	1000	200	3804.428	0	0.000	19	0.007	19	0.007	19	0.007	19	0.007	19	0.007
1	1000	400	2654.922	19	0.011	19	0.011	19	0.011	19	0.010	19	0.010	0	0.000
3	1000	400	2668.497	19	0.011	19	0.011	18	0.011	0	0.000	19	0.010	19	0.010
6	1000	400	2684.903	0	0.000	19	0.011	19	0.011	19	0.011	19	0.011	19	0.011
1	1000	600	2055.653	18	0.013	18	0.013	18	0.012	18	0.012	18	0.012	0	0.000
3	1000	600	2065.943	18	0.013	18	0.013	18	0.012	0	0.000	18	0.012	18	0.012
6	1000	600	2078.446	0	0.000	18	0.012	18	0.012	18	0.012	18	0.012	18	0.012

Appendix D : Supply and Exhaust Bottom Connected. Case 03

Fire Floor	Fire Flow (l/s)	Fire Temperature (C)	Fire Pressure (Pa)	Sixth Floor		Fifth floor		Fourth floor		Third floor		Second floor		First floor	
				Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution
3	300	200	347.322	0	0.000	0	0.000	0	0.000	0	0.000	2	0.002	2	0.002
6	300	200	347.661	0	0.000	2	0.002	2	0.002	2	0.002	2	0.002	2	0.002
1	300	400	246.014	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000
3	300	400	245.592	0	0.000	0	0.000	0	0.000	0	0.000	2	0.003	2	0.003
6	300	400	245.768	0	0.000	2	0.004	2	0.003	2	0.003	2	0.003	2	0.003
1	300	600	190.875	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000
3	300	600	190.474	0	0.000	0	0.000	0	0.000	0	0.000	2	0.004	2	0.004
6	300	600	190.571	0	0.000	2	0.004	2	0.004	2	0.004	2	0.004	1	0.003
1	600	200	1382.176	1	0.001	2	0.001	3	0.002	3	0.002	4	0.002	0	0.000
3	600	200	1381.665	1	0.001	2	0.001	3	0.002	0	0.000	6	0.004	7	0.004
6	600	200	1383.834	0	0.000	5	0.003	5	0.003	6	0.003	6	0.003	6	0.004
1	600	400	975.456	1	0.001	2	0.002	3	0.002	3	0.003	4	0.004	0	0.000
3	600	400	974.941	1	0.001	2	0.002	3	0.002	0	0.000	6	0.006	6	0.006
6	600	400	976.286	0	0.000	5	0.005	5	0.005	6	0.005	6	0.005	6	0.005
1	600	600	755.074	1	0.001	2	0.002	3	0.003	3	0.004	4	0.004	0	0.000
3	600	600	754.561	1	0.001	2	0.002	3	0.003	0	0.000	6	0.007	6	0.007
6	600	600	755.465	0	0.000	5	0.006	5	0.006	5	0.006	6	0.006	6	0.006
1	1000	200	3827.994	8	0.003	9	0.003	10	0.004	10	0.004	11	0.004	0	0.000
3	1000	200	3827.537	8	0.003	9	0.003	9	0.003	0	0.000	16	0.006	16	0.006
6	1000	200	3834.673	0	0.000	14	0.005	14	0.005	14	0.005	14	0.005	14	0.005
1	1000	400	2698.266	8	0.005	9	0.005	10	0.005	10	0.006	11	0.006	0	0.000
3	1000	400	2697.726	8	0.005	9	0.005	10	0.005	0	0.000	15	0.009	15	0.009
6	1000	400	2702.543	0	0.000	13	0.007	13	0.007	13	0.007	13	0.008	14	0.008
1	1000	600	2086.092	8	0.006	9	0.006	10	0.006	10	0.007	11	0.007	0	0.000
3	1000	600	2085.516	8	0.005	9	0.006	10	0.006	0	0.000	15	0.010	15	0.010
6	1000	600	2089.094	0	0.000	13	0.009	13	0.009	13	0.009	13	0.009	13	0.009

Appendix E : Converted Supply Exhaust System. Case 04

Fire Floor	Fire Flow (l/s)	Fire Temperature (C)	Fire Pressure (Pa)	Sixth floor		Fifth floor		Fourth floor		Third floor		Second floor		First floor	
				Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution
1	300	200	286.662	0	0	0	0	0	0	0	0	0	0	0	0
3	300	200	285.844	0	0	0	0	0	0	0	0	0	0	0	0
6	300	200	286.475	0	0	0	0	0	0	0	0	0	0	0	0
1	300	400	186.496	0	0	0	0	0	0	0	0	0	0	0	0
3	300	400	185.916	0	0	0	0	0	0	0	0	0	0	0	0
6	300	400	186.337	0	0	0	0	0	0	0	0	0	0	0	0
1	300	600	132.908	0	0	0	0	0	0	0	0	0	0	0	0
3	300	600	132.458	0	0	0	0	0	0	0	0	0	0	0	0
6	300	600	132.766	0	0	0	0	0	0	0	0	0	0	0	0
1	600	200	1337.088	0	0	0	0	0	0	0	0	0	0	0	0
3	600	200	1334.234	0	0	0	0	0	0	0	0	0	0	0	0
6	600	200	1337.07	0	0	0	0	0	0	0	0	0	0	0	0
1	600	400	930.425	0	0	0	0	0	0	0	0	0	0	0	0
3	600	400	928.42	0	0	0	0	0	0	0	0	0	0	0	0
6	600	400	930.381	0	0	0	0	0	0	0	0	0	0	0	0
1	600	600	710.199	0	0	0	0	0	0	0	0	0	0	0	0
3	600	600	708.653	0	0	0	0	0	0	0	0	0	0	0	0
6	600	600	710.14	0	0	0	0	0	0	0	0	0	0	0	0
1	1000	200	3792.997	0	0	0	0	0	0	0	0	0	0	0	0
3	1000	200	3785.67	0	0	0	0	0	0	0	0	0	0	0	0
6	1000	200	3793.884	0	0	0	0	0	0	0	0	0	0	0	0
1	1000	400	2663.121	0	0	0	0	0	0	0	0	0	0	0	0
3	1000	400	2657.976	0	0	0	0	0	0	0	0	0	0	0	0
6	1000	400	2663.719	0	0	0	0	0	0	0	0	0	0	0	0
1	1000	600	2050.95	0	0	0	0	0	0	0	0	0	0	0	0
3	1000	600	2046.987	0	0	0	0	0	0	0	0	0	0	0	0
6	1000	600	2051.393	0	0	0	0	0	0	0	0	0	0	0	0

Appendix F : Open Duct Supply System. Case 05

Fire Floor	Fire Flow (l/s)	Fire Temperature (C)	Fire Pressure (Pa)	Sixth Floor		Fifth floor		Fourth floor		Third floor		Second floor		First floor	
				Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution
1	300	200	282.322	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000
3	300	200	283.38	0	0.000	0	0.000	0	0.000	0	0.000	3	0.003	3	0.003
6	300	200	285.732	0	0.000	2	0.003	2	0.003	2	0.003	2	0.003	2	0.003
1	300	400	185.274	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000
3	300	400	186.342	0	0.000	0	0.000	0	0.000	0	0.000	3	0.005	2	0.005
6	300	400	188.375	0	0.000	2	0.004	2	0.004	2	0.004	2	0.004	2	0.004
1	300	600	133.714	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000
3	300	600	134.778	0	0.000	0	0.000	0	0.000	0	0.000	2	0.005	2	0.005
6	300	600	136.639	0	0.000	2	0.005	2	0.005	2	0.005	2	0.005	2	0.005
1	600	200	1300.34	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000
3	600	200	1304.229	0	0.000	0	0.000	0	0.000	0	0.000	4	0.002	4	0.002
6	600	200	1310.679	0	0.000	4	0.002	4	0.002	4	0.002	4	0.002	4	0.002
1	600	400	901.158	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000
3	600	400	904.268	0	0.000	0	0.000	0	0.000	0	0.000	4	0.004	4	0.004
6	600	400	909.183	0	0.000	4	0.004	4	0.004	4	0.004	4	0.003	4	0.003
1	600	600	685.224	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000
3	600	600	687.916	0	0.000	0	0.000	0	0.000	0	0.000	4	0.004	4	0.004
6	600	600	691.997	0	0.000	4	0.004	4	0.004	4	0.004	4	0.004	4	0.004
1	1000	200	3707.802	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000
3	1000	200	3720.08	0	0.000	0	0.000	0	0.000	0	0.000	3	0.001	3	0.001
6	1000	200	3737.659	0	0.000	4	0.002	4	0.001	4	0.001	3	0.001	3	0.001
1	1000	400	2597.288	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000
3	1000	400	2606.324	0	0.000	0	0.000	0	0.000	0	0.000	4	0.002	4	0.002
6	1000	400	2618.788	0	0.000	4	0.002	4	0.002	4	0.002	4	0.002	3	0.002
1	1000	600	1995.692	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000
3	1000	600	2002.913	0	0.000	0	0.000	0	0.000	0	0.000	4	0.003	4	0.002
6	1000	600	2012.706	0	0.000	5	0.003	4	0.003	4	0.003	4	0.003	4	0.002

Appendix G : Open Duct Exhaust System. Case 06

Fire Floor	Fire Flow (l/s)	Fire Temperature (C)	Fire Pressure (Pa)	Sixth Floor		Fifth floor		Fourth floor		Third floor		Second floor		First floor	
				Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution	Smoke Liters (l/s)	Dilution
1	300	200	386.359	0	0.000	0	0.000	0	0.000	9	0.011	55	0.068	0	0.000
3	300	200	386.237	0	0.000	0	0.000	0	0.000	0	0.000	32	0.039	32	0.039
6	300	200	386.281	0	0.000	13	0.016	13	0.016	13	0.016	13	0.016	13	0.016
1	300	400	286.549	0	0.000	0	0.000	0	0.000	0	0.000	57	0.106	0	0.000
3	300	400	287.289	0	0.000	0	0.000	0	0.000	0	0.000	28	0.052	28	0.052
6	300	400	287.155	0	0.000	11	0.021	11	0.021	11	0.021	11	0.021	11	0.021
1	300	600	233.992	0	0.000	0	0.000	0	0.000	0	0.000	50	0.110	0	0.000
3	300	600	234.88	0	0.000	0	0.000	0	0.000	0	0.000	24	0.054	24	0.054
6	300	600	234.659	0	0.000	10	0.021	10	0.021	10	0.021	10	0.021	10	0.021
1	600	200	1397.785	0	0.000	0	0.000	33	0.020	59	0.037	59	0.036	0	0.000
3	600	200	1399.688	0	0.000	0	0.000	34	0.021	0	0.000	59	0.036	59	0.036
6	600	200	1407.006	0	0.000	30	0.019	30	0.019	30	0.019	30	0.019	30	0.019
1	600	400	996.886	0	0.000	0	0.000	10	0.009	69	0.064	69	0.064	0	0.000
3	600	400	997.892	0	0.000	0	0.000	10	0.010	0	0.000	69	0.064	69	0.064
6	600	400	1002.957	0	0.000	30	0.028	30	0.028	30	0.028	30	0.028	30	0.027
1	600	600	778.532	0	0.000	0	0.000	0	0.000	68	0.075	77	0.084	0	0.000
3	600	600	780.052	0	0.000	0	0.000	0	0.000	0	0.000	72	0.079	72	0.079
6	600	600	784.266	0	0.000	29	0.032	29	0.032	29	0.032	29	0.032	29	0.032
1	1000	200	3800.611	4	0.001	65	0.024	65	0.024	64	0.024	64	0.024	0	0.000
3	1000	200	3805.996	4	0.002	65	0.024	65	0.024	0	0.000	64	0.024	64	0.024
6	1000	200	3828.303	0	0.000	53	0.019	52	0.019	52	0.019	52	0.019	52	0.019
1	1000	400	2686.078	0	0.000	36	0.020	74	0.042	74	0.041	74	0.041	0	0.000
3	1000	400	2689.637	0	0.000	37	0.021	74	0.041	0	0.000	74	0.041	74	0.041
6	1000	400	2708.132	0	0.000	52	0.029	52	0.029	52	0.029	52	0.029	52	0.029
1	1000	600	2082.378	0	0.000	8	0.005	83	0.055	83	0.055	83	0.055	0	0.000
3	1000	600	2084.968	0	0.000	9	0.006	83	0.055	0	0.000	82	0.054	82	0.054
6	1000	600	2098.797	0	0.000	52	0.034	52	0.034	51	0.034	51	0.034	51	0.034