Smoke and Fire Gases Venting in Large Industrial Spaces and Stores

Polina Gordonova

Division of Building Services
Department of Building and Environmental Technology
Lund Institute of Technology
Lund University, 2004
Report TVIT--04/3001

Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 101 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 5 530 employees and 34 000 students attending 60 degree programmes and 850 subject courses offered by 89 departments.

Smoke and Fire Gases Venting in Large Industrial Spaces and Stores

Polina Gordonova

Keywords

Industrial fires, smoke management, smoke vent, fire flow, fire pressure, fire simulation, ventilation ducts.

Abstract

The present study is focused on the problem of smoke evacuation and the possibility of operating the fans during different fires in large spaces and buildings. Various studies on fire hazards have shown that the predominant cause of hazard is smoke, not the temperatures. Management of smoke has the primary goal of facilitating safe egress in the event of fire, but it is also important in surviving property that costs more nowadays then the cost of the building itself. Thus, the control and removal of smoke and fire gases from the building is a vital component in any fire protection scheme. Smoke control and smoke management are two major ways of dealing with the problem. The purpose of smoke management is to create a smoke layer above the occupied level. According to building regulations and codes in different countries this can be achieved by providing buildings with roof mounted smoke and heat openings, which are opened by fusible links and also automatically after detecting fire with the help of different types of detectors, as well as by exhausting smoke with roof mounted fans. In Sweden, both types of smoke venting are recommended depending on the fire class of the space. Additional mechanical exhaust ventilation of the fire volume, providing from four to six air changes per hour, is also recommended. It is expected that this rate of air flow will remove smoke at approximately the same rate as it is produced. This system is expected to maintain the interface between the smoke layer and the breathing zone sufficiently high above floor level for people to leave the space. Makeup air can be introduced mechanically or in the natural way due to the under pressure in the compartment.

However, the possibility of using the ordinary ventilation systems during fire development has not been studied enough and it is just beginning to take a proper place as a fire protection tool.

Smoke ventilation combined with the use of ordinary ventilation systems and opened doors in a single space was studied. The research is based on calculations carried out using the computer programs PFS for static flow calculations and SIMNON for dynamic fire simulations.

The combination of wind pressure on the building and the airtightness of the building along with opening of doors, windows in the walls and fire vents on the roof can result in great variations in pressure. The results of these simulations for the steady fires and t^2-fires with heat release rate of 2,5 MW, 5 MW and 25MW respectively are presented. Both unsprinklered fires and sprinklered fires were studied. Method for estimating the resulting pressure in a building are presented. Up-to-date knowledge about the external airtightness of the examined buildings, and the results of the analyses of the function of natural smoke ventilators in the case of fire are presented.

Different solutions for the evacuation of smoke with the help of ventilation systems are given. Thirteen different cases have been studied. These cases comprise different combinations of opened contra closed openings on the windward and/or leeward sides of walls, roof smoke vents of different areas exposed to different outdoor temperatures and wind velocities. Those thirteen cases were integrated with thirteen different variations in operating smoke fans, ordinary ventilation systems and their combined operation. The main resulting parameters of the analysis are interpreted in terms of "wrong"/reversed flow through smoke vents and a combination of different measures for smoke evacuation is supplemented with variations in ordinary fan function.

One of the most common problems in evacuating hot smoke with the help of the ventilation systems is the temperature endurance of the fans. The results of different tests on fan motors operating at high temperatures are presented.

Contents

List of symbols and definitions

Symbols

Unless otherwise started, the following symbols are used throughout this document:

A	area, [m^2]
b	width, [m]
c	specific heat of incompressible substance, [J/kg K]
C	flow coefficient, [-]
d	diameter, [m]
D	optical density per meter, [m^{-1}]
E_y	elastic (Young's) modulus, [N/m^2]
E	energy, [J]
f	coefficient of volumetric expansion, [(m^3/s)/MW]
h	heat transfer coefficient, [W/m^{2}K]
l	length, [m]
m_b	mass flow rate, [kg/s]
p	pressure, [Pa]
q	volume flow rate, [m^3/s]
Q	heat rate, [kW]
R	resistance, [-]
s	visibility range, [m]
t	time, [s]
T	temperature, [°C (K)]
v	velocity, [m/s]
V	volume, [m^3]
z	height, [m]
Re	Reynolds number, [-]
ΔM	mass loss of sample, [g]

Greek letters

α	characteristic value for a certain fire progress, $[kW/s^2]$	
β	thermal expansion, $[K^{-1}]$	
η	viscosity, $[N\ s/m^2]$	
λ	thermal conductivity, $[W/mK]$	
ν	kinematic viscosity, $[m^2/s]$	
ρ	density, $[kg/m^3]$	
σ	thermal stress, $[N/m^2]$	
Δ	increment of	

Definitions

For the purpose of this dissertation, [The SFPE Handbook of Fire Protection Engineering, 7th edition] was used as the main material to describe research in this domain. Nevertheless, some other terms has been used in order to express more recent concepts. The definitions of this dissertation are as follows:

Air leakage:

The uncontrolled flow of air through a component of the building, or the building envelope itself, when a pressure difference is applied across the compartment.

Air tightness:

A general descriptive term for the air permeability resistance of a building.

Building envelope:

The inside of the exterior surfaces of the building.

Buoyant flow:

A gas flow which is caused directly or indirectly by gravity.

Compartment fire:

Fire in enclosed spaces, which are commonly thought as rooms in a building.

Constrained fire:

The availability of both fuel and oxygen are considered.

Fire flow:

Fire gas flow caused by temperature expansion of the heated gas in the fire room in the case of fire.

Fire plume:

The generally turbulent buoyant flow, which includes any flames.

Forced (mechanical) ventilation:

Ventilation by means of fans.

Natural ventilation:

Ventilation using only natural driving forces such as differences in air temperature and density, wind pressure.

Overflash:

The transition from a growing fire to a developed fire in which all combustible items in the compartment are involved in fire.

Smoke control system:

Is an engineered system using fans providing pressure differences and air flows in order to limit smoke movement across barriers.

Smoke management system:

Is an engineered system using different methods in order to modify or drive smoke movement singly or in combination.

Steady fire:

Fuel is burning at a constant rate.

Ventilation:

The process of supplying and removing air intentionally by natural or forced (mechanical) means to and from any space.

Unconstrained fire:

Fuel is burned without regard for oxygen availability.

Preface and acknowledgements

Summary

The following study examines the problem of smoke evacuation through roof vents and the possibility of operating the ordinary fans during different fires in large spaces and buildings. Various studies on fire hazards have shown that the predominant cause of hazard is smoke, not the temperatures. Management of smoke has the primary goal of facilitating safe egress in the event of fire, but it is also important in surviving property that costs more nowadays then the cost of the building itself. Thus, the control and removal of smoke and fire gases from the building is a vital component in any fire protection scheme. Smoke management is the way of dealing with the problem in the single space. There are two major types of smoke evacuation - roof mounted smoke and heat openings (so called smoke vents) and roof-mounted fans. In Sweden, both types of smoke venting are recommended depending on the fire class of the space. The reliability of such smoke vents has been discussed in the profession. Poor operation as well as the failure of the smoke vents to open have been often reported. These faults depend partly on insufficient control and maintenance and wrong control, and, partly, on complicated pressure conditions due to wind, fire, ventilation and buoyancy. Smoke vents do not manage this situation. The same factors affect the operation of smoke fans. Although the problem is well known, the probability of this and the conditions which lead to such a phenomenon have not been fully examined yet. However, the proper operation of roof mounted smoke vents and the possibility of using the ordinary ventilation systems during fire development have not been studied enough and they are just beginning to take a proper place as a fire protection tool.

Ordinary ventilation systems normally shut down in the event of fire.

The main goal of this study is to examine the ability of roof mounted vents to evacuate smoke and to evaluate the effectiveness of roof fans in the single industrial or storage building. Smoke ventilation combined with the use of ordinary ventilation systems and opened doors for make-up air in a single space were studied.

The results are analyzed in terms of right/wrong airflow direction through the roof vents.

Whether or not smoke will be evacuated from the space is determined by:

- the heat released by fire,
- wind pressure on the space as a whole,
- the operation of the sprinkler system,
- the airtightness of buildings along with
- the area and layout of smoke vents and openings in the walls and, if needed,
- the layout and properties of ventilation systems and roof mounted smoke fan(s).

In this connection it is extremely significant to assess the relationship between all the factors described above in order to evaluate the resulting pressure in the typical space. The point is to give recommendations on good practice to diminish or even eliminate the risk of reversed air-smoke flow through roof vents or to replace them with roof mounted fan(s). The possibility of using the fan(s) of the ordinary ventilation system is also taken into account in the analysis.

The research is based on calculations carried out using the computer programs PFS for static flow calculations and SIMNON for dynamic fire simulations.

The state of knowledge and research publications in this regard have been searched through different databases in science and technology and via several search programs on the Internet. In addition, current publications on this matter in different scientific and technical periodicals were followed. As the study is interdisciplinary in nature and comprises different fields of engineering knowledge such as fire protection engineering, building services and building science, publications within both the fire protection and building science periodicals have been followed.

Owing to the variety of different possible fire scenarios in the studied types of spaces, it is necessary to evaluate those that are most probable. In order to assess the resulting fire mass flow, steady fires with heat release rates of 2,5 MW, 5 MW and 25MW respectively were examined. Two different ways of fire flow evaluation according to Takeyoshi Tanaka, Toshio Yamana and Heskestad are complemented with my own simplified equation.

Some statistics on natural smoke vents in different industries in Sweden are presented in the report. The proportion of roof mounted smoke vents that opened during the control varies between 67% and 93% of the total number. The usual causes of the failure of smoke vents to open are analysed and compiled in the study.

The results of these simulations for the steady fires and t^2-fires with heat release rate of 2,5 MW, 5 MW and 25MW respectively are presented.

The combination of wind pressure on the building and the airtightness of the building along with opening of doors, windows in the walls and fire vents on the roof can result in great variations in pressure.

Evaluation of the resulting pressure is based on the analysis of all pressures inside and outside the examined space, such as:

- fire pressure due to expansion;
- bouyancy;
- wind pressure;
- the cooling effect of sprinklers on the indoor temperature and, thus, on the fire pressure and
- ventilation fan pressure and the layout of the ventilation system(s).

As usual the pressure rise is described as a function of the mean temperature in the space and the temperature rise.

Rate of rise of temperature, B, is assumed to be a constant value in this equation. As a matter of fact, B (K/s) is not a constant as it also depends on heat released by the fire and, thus, on temperature rise. Analysis of this phenomenon is presented in the study. A model to estimate pressure due to expansion and computer simulations for both the t^2-fires and the steady fires are introduced here. A computer program SIMNON is used for this purpose.

SIMNON is a computer program for the simulation of mathematical, non-linear relationships between the input and output signals in a system, as well as the integration of several dynamic subsystems into one total system. SIMNON is made by SSPA Systems, a group within SSPA Maritime Consulting AB. Time dependant changes in temperature, pressure and mass flow for steady and t^2-fires with heat release rates of 1 MW, 2.5 MW and 5 MW are presented in the paper.

For the purpose of this study the sizes of air leakage paths in industrial buildings constructed in different countries are complicated. There is an essential difference in such data from one country to another. Swedish construction traditions and airtightness requirements differ from those in the USA. Airtightness requirements in USA industrial spaces can be five to ten times greater than those in corresponding spaces in Sweden.

For the purpose of this study the size of air leakage paths for Swedish buildings is determined by requirements in the Swedish Building Regulations, i.e. air leakage is assumed to be 6 m^3/h, m^2 relating to the surface area of the buildings envelope.

The resulting internal pressure determines flow direction through a smoke vent. A model evaluating this phenomenon is presented in the study. The resulting internal pressure determines flow direction through the vent. The study estimates this internal pressure as a function of a resulting internal wind factor called here equivalent indoor wind factor. A new term "equivalent indoor wind factor", a model for its evaluation and theoretical equations are introduced in this analysis. If the equivalent internal wind factor is smaller than any wind factor outside close to an opening or a leakage path then there will be an inflow into the space, and if it is larger, then an outflow from the space. The equation presented here can only be solved analytically for two surfaces; for other surfaces numerical methods have to be used. Analysis begins with evaluation of the resulting pressure in a space without fire and ventilation. Further, two more cases were studied: a fire case with some imbalance in ventilation.

The resulting internal pressure in a real space in case of fire, with ordinary ventilation systems in operation and opened smoke vents on the roof and openings in the walls for make-up air was examined. Vents of different areas were tested.

The method focuses on simulation of pressure conditions around and inside a space of a certain airtightness exposed to wind at different outdoor temperatures during a fire. The ordinary ventilation systems are running. For this purpose a computer program PFS, which treats arbitrary flow systems, was used. This program, developed and written by Lars Jensen, is based on the semi graphical circuit drawings and treats arbitrary flow systems of any structure and layout, any media, and any problem: design or investigation. A "real" and a schematic models are presented in the study. The examined space has doors in the walls for make-up air, smoke vents on the roof, roof mounted smoke fan and supply and exhaust ventilation systems.

The study was made "step-by-step":

- step 1 - "cold" case without ventilation system,
- step 2 - fire case with some ventilation imbalance,
- step 3 - fire case with either supply or exhaust ventilation system in operation,
- step 4 - real fire case with the ordinary supply-exhaust ventilation system along with variations in the opening of the smoke vents and/or roof mounted fan.

Different design parameters were chosen for the study. These parameters include

- size of the space examined, area of leakage paths, type of fan, number and area of smoke vents, smoke fan characteristics, exhaust and supply ventilation systems, weather data, fire and smoke layer characteristics, and values of ventilation system characteristics,
- climatic data (outdoor temperatures, wind velocities),
- fire behaviour (fire scenario, maximal heat released rate),
- smoke layer parameters (height and maximal temperature),
- exhaust, supply and smoke fans (fan curve).

An important parameter in this study is the cooling effect of sprinkler on the ambient air. There are numerous studies on the interaction between sprinklers and the operating of smoke vents. The focus of these studies is sprinklers, and they analyse negative and positive claims in this connection for sprinkler operation.

The most common negative claims are as follows:

- smoke vents can delay sprinkler activation and as a result can cause large fires by diminishing gas temperatures at ceiling level,
- smoke vents can increase the number of activated sprinklers as the result of the above presented cause,
- smoke vent flow rates can be insufficient due to diminished buoyancy and thus are not cost effective.

There are studies that prove the above-presented issues, and also studies that question them.

In this study an attempt was made to evaluate this issue inversely. Smoke vents in operation are the focus here. The cooling effect of sprinklers on ambient air and the smoke layer seems to be the most important expected result to be evaluated from this point of view. The resulting lower indoor temperatures give rise to lower buoyancy values and lower pressure due to expansion. Different studies have examined a single sprinkler of varied capacity and the results of these studies have been presented and analysed. Rregression analysis has resulted in equations. Alpert's equation for temperature difference between the smoke layer and ambient indoor air is limited to the steady fire case.

Another phenomenon due to the cooling effect of sprinklers on the ambient air and smoke is a reversed flow through smoke vents as a result of the indoor temperature being somewhat lower than the outdoor temperature. This can be expected during spring/summer.

The possibility of using a modified and upward straightened sprinkler in order to improve the smoke-extraction function of a smoke vent is studied in the report. The problem with an upward straightened sprinkler is that airflow slows down and stops at some range due to gravity. Water drops fall down through this upward going airflow. The result of this interaction is examined and presented in the study.

The possibility of using ordinary ventilation systems for smoke extraction is analysed in this report. The ability of the ventilation system to evacuate fire gases is limited by its own maximum service temperature. This problem was analysed here. The most characteristic parameters for different parts of a motor such as windings, ball bearing, belt etc. are presented in this study. The problem of thermal endurance of a motor is examined with the help of three models:

- at constant mass airflow,
- at constant volume airflow and
- at constant pressure drop.

Analysis with constant mass airflow through the fan results in an overestimate because under constant mass airflow conditions density is halved and velocity doubles when temperature doubles.

Under constant volume airflow conditions the mass airflow from the fire room is underestimated because density and therefor mass airflow, as well as pressure, are halved when temperature doubles.
Analysis of the problem based on constant pressure drop assumes that rv^2 is similar both for an ordinary operation and in case of fire.

The temperature-dependent power demand of a fan is analyses here for an uncontrolled, air-volume controlled and pressure-drop controlled ventilation fan.

The report examines the static and the dynamic thermal endurance of a motor with the help of a model.
Some of the results from three different laboratory tests, with fan motors operating at high temperatures, are presented.

One of the ways to improve the function of smoke vents is to ensure that pressure in a space is positive. This could be achieved by running the supply ventilation system by displacement (not of the mixing type) only. In the case with the mixing supply ventilation, smoke may possibly spread down to the floor. The layout of the ventilation system could be adjusted

for the purpose of using it as smoke ventilation system. A simple measure in this connection is to choose an exhaust fan with a higher than usual temperature endurance. Increasing the speed of the fan for a relatively short period can also be a possible measure.

Alternatively, ordinary exhaust fans may be replaced by special smoke fans, the pressure loss in the exhaust ventilation plant including filter and heat exchange unit can be considerable, and the ordinary air flow can be too low.

One more method can be to use the supply duct network for the purpose of smoke extraction. This can be reasonable for the mixed ventilation system but is less suitable for the ventilation system by displacement. In this case both ventilation ducts can be connected to one or several smoke fans. In this way the new airflow could be double the ordinary airflow.

Another opportunity is to treble the ordinary airflow by choosing a suitable smoke fan. This means that an ordinary ventilated space with an air change rate of two -/h can be ventilated in ten minutes. The size of the ventilation ducts can be made somewhat bigger than in the ordinary case.

All the above cases were examined in the study. Operation of ordinary ventilation systems in combination with smoke fans and smoke vents of variable area, at different outdoor temperatures, is presented here. All these measures, applied in the design space at different outdoor climatic parameters, were studied and are presented in the report. The results show that there is longer time for egress and less damage to equipment because the smoke layer rises slowly due to improved smoke extinction.

The resulting parameters from simulations are airflow, pressure and pressure loss and airflow direction through a smoke vent. This provides greater opportunities for further and more detailed analysis of pressure versus airflow conditions in a certain studied space.

The problem examined in the present study appears complex, and the assumptions, made with a certain lack of knowledge and a paucity of empirical data, cannot diminish the uncertainty of the results obtained. The results should not therefore be interpreted as some sort of total solution to the elimination of inverted smoke flow through a smoke vent, but should be considered as a guidance and help in such types of analysis.

In this particular study a simple method and a model were examined. This method is a tool to evaluate which combination of different measures for smoke management is the optimum for the particular space located at the particular site.

Sammanfattning

Projektet undersöker rökevakuering via termiska rökventilatorer och möjligheter att utnyttja befintliga ventilationssystem i stora industri- och lagerbyggnader. Rökgasutvecklingen i en brinnande byggnad är en stor fara och ett stort problem. Rök- och brandgaser hindrar utrymning, skadar byggnader och dess innehåll samt försvårar släckarbetet och är farliga för både personer som normalt vistas i den brinnande lokalen samt för räddningspersonalen. Brandventilation rekommenderas i industri- och lagerbyggnader av de Svenska Byggreglerna. Det finns två olika system för brandgasventilation: ett termiskt (via brandventilatorer) och ett mekaniskt (med hjälp av brandgasfläktar). Icke fungerande eller dåligt fungerande brandventilatorer beskrivs ofta i olika rapporter. Brister i brandventilation beror delvis på dåligt underhåll och delvis på komplicerade vindtryck, brandtryck, ventilationstryck och termiskt tryck kring och i byggnaden. Brandventilatorerna räcker inte till. Samma faktorer påverkar brandgasfläktsfunktion också. Trots att problemet är välkänt, är sannolikheten av att fenomenet inträffar och villkor som leder till detta inte utforskat än. Normalt stänger man av befintliga ventilationssystem i den brinnande byggnaden så fort branden upptäcks. Projektets syftet är att utreda hur termiska brandventilatorer, öppning av portar och befintliga ventilationssystem kan samverka för att ge bästa effekt. Uppgiften är också att undersöka om och i så fall hur en avvägning mellan termiska brandventilatorer, brandgasfläktar och ett eventuellt förstärkt ventilationssystem skall göras. Resultat redovisas i form av andel "felfungerande" (inströmning istället för utströmning) brandventilatorer i procent.

Hur rökevakuering kommer att ske beror på

- utvecklad värmeeffekt,
- vindtryck on byggnaden i sin helhet,
- sprinkler,
- byggnadens läckage och area av termiska brandventilatorer och öppningar i väggar för ersättningsluft, och

- brandgasfläktar och ventilationssystemets egenskaper.

I detta sammanhang är det viktigt att uppskatta ett samband mellan alla de ovan beskrivna typiska faktorerna för att värdera resulterade rökevakuering samt att ge rekommendationer för minskning eller uteslutning av risk för omvänt flöde via rökgasventilatorer.

Den här analysen är baserat på databeräkningar gjord med hjälp av två dataprogram: PFS för statiska flödesberäkningar och SIMNON för dynamiska simuleringar.

Olika databaser i vetenskap och teknologi genomsöktes, vetenskapliga artiklar har genomlästs samt olika sökprogram i Internet har använts för att skaffa information om kunskaper berörande brandgasevakuering vid händelse av en brand. Dessutom har vetenskapliga och tekniska tidskrifter inom aktuellt ämnesområde följts.

Många olika tänkbara brandscenario i de undersökta lokaltyperna leder till uppskattning av de mest sannolika. För uppskattningen av utvecklade brandflöde konstanta bränder med 2.5 MW, 5 MW och 25 MW utvecklat värmeeffekt har studerats. Två olika sätt att beräkna brandflöde enligt Takeyoshi Tanaka, Toshio Yamana's och Heskestad har kompletterats med en egen förenklad ekvation.

Statistisk uppskattning av brandgasventilatorers funktion i några utav befintliga industrianläggningar i Sverige är presenterat i rapporten. Mellan 67% och 93% av alla testade brandventilatorer har öppnats under kontrolltillfällen. Orsaker till detta har också sammanställs.

Båda t^2 och konstanta brandscenario för 2.5 MW, 5 MW och 25 MW och även 1 MW utvecklat värmeeffekt har studerats.

Uppskattning av de resulterande tryckförhållanden bygger på analys av olika tryck inom och omkring en brinnande anläggning såsom

- brandtryck p g a termik expansion,
- bouayncy (tryckskillnad som resultat av temperaturskillnad inne och ute),
- vindtryck,
- sprinklers inverkan på inre temperatur och, som foljd, på brandtryck och
- "ventilationstryck", d v s tryckförhållande inom anläggning p g a ventilationsobalans skapat av fläktar.

Uppskattning av brandtryck vanligtvis görs enligt antagande om att detta beror på medel innetemperatur, konstant ökning av temperatur och förhållande mellan olika geometriska mått av öppningar, själva lokalen och brandgaslager. Ökning av temperatur, B, antas vara ett konstantvärde i detta sammanhang. Parameter B är inte konstant i själva verket och i sin

tur också beror på brandeffektutveckling. Egen analys av detta fenomen presenteras i rapporten. En modell för att uppskatta tryck p g a expansionen och databeräkningar för båda konstanta och t^2-bränder med hjälp av dataprogram SIMNON baserade på denna modell presenteras här.

SIMNON är ett dataprogram för simuleringar av matematiska icke linjära problem och för koppling ihop flera dynamiska undersystem i ett system. SIMNON är markerat av SSPA Systems, en grupp inom SSPA Maritime Consulting AB. Tryck-, temperatur- och massflödesförändringar presenteras för konstanta och t^2-bränder med 1 MW, 2.5 MW och 5MW utvecklad brandeffekt.

För att uppskatta yttre och inre täthet av analyserade lokaler har en sammanställning av kunskap beträffande läckage av hus byggda i olika länder genomförts. Det råder stor skillnad mellan olika länder i läckage area av anläggningar av samma typ. Läckage area av industriella anläggningar i USA, till exempel, kan vara fem till tio gånger större än läckage area i motsvarande byggnader i Sverige. För den här analysen, BBR 99:s krav på hur stor en icke bostadsbyggnads otäthet högst får vara, tillämpad på hela omslutande klimatskala, antas dimensionerande för det här projektet.

Den resulterade flödesriktningen via brandventilatorer beror på det resulterande tryckförhållandet inom anläggningen gentemot det fria. Analysen börjar med undersökningen av det resulterade trycket inom icke brinnande anläggning utsatt för vindpåverkan. En egen modell för att uppskatta fenomenet presenteras i rapporten. En ny term "ekvivalent inre vind faktor", en modell och teoretiska ekvationer för denna introduceras här. Ifall den ekvivalenta inre vind faktorn är mindre än någon utav yttre vind faktorer, kommer uteluft att strömma in i anläggningen genom alla sorts öppningar. Ekvationen kan tillämpas analytiskt för två ytor, för fler ytor numeriska metoder bör användas. Ekvationen och modellen är framtagna för ett kallt fall och ventilation i balans eller utan ventilation alls. Ytterligare två fall, ett för brandfall med ventilation i balans och ett för brandfall med ventilation i obalans, har studerats.

Det resulterande tryckförhållandet i en verklig anläggning vid händelse av en brand med ordinarie ventilationssystem i drift och öppnade brandventilatorer på tak och portar i väggar har testats. Areor av dessa öppningar har varierats.

Arbetsmetoden bygger på att simulera tryckförhållandena kring och inom en byggnad av viss täthet vid händelse av en viss brand utsatt för vindtryck och vissa inom- och utomhus temperaturskillnader parallellt med fungerade befintliga från– och tilluftsventilationssystem. Detta har

gjorts med hjälp av beräkningsprogrammet PFS. PFS är ett statiskt halvgrafiskt datorprogram för beräkning av diverse flöde. Programmet är skrivit och utvecklat av Lars Jensen, professor på Lunds Tekniska Högskola, Lunds universitet, Sverige. "Verklig" och dataanpassad modell av en byggnad presenteras i rapporten. Den studerade byggnaden har dörrar och portar för ersättningsluft, brandventilatorer på tak, brandgasfläkt och till- och frånlufts ventilationssystem.

Analysen är gjord enligt "steg efter steg" principen för

- steg 1 - ett kallt fall utan ventilation,
- steg 2 - ett brandfall med ventilationsobalans,
- steg 3 - ett brandfall med antingen till- eller frånluftssystem i drift,
- steg 4 - ett brandfall med ordinarie till- och frånluftssystem i drift kombinerad med variationer av öppning av brandventilatorer och/ eller brandgasfläkt i drift.

Ett antal dimensionerande parametrar är valda för att genomföra denna analys. Dimensionerande parametrar omfattar

- anläggnings parametrar (mått, läckage area, typ av tak, antal och area av brandventilatorer, brandfläkt, till- och frånluftssystem),
- klimat data (ute temperaturer, vindhastigheter),
- brandförlopp (brandscenario, maximal utvecklad brandeffekt),
- brandgaslager (höjd och maximal temperatur),
- till- och frånluftsfläktar, brandgasfläkt (fläktkurva).

En viktig parameter i det studerade fenomenet är avkylnings effekt på inneluft i sprinklade anläggningar. De finns mängder av studier om sprinklers funktion med samtidig öppning av brandventilatorer. Dessa studier är inriktade på sprinkler och de samlar och analyserar fördelar och nackdelar med att öppna brandgasventilatorer vid fungerande sprinkler. De mest vanliga nackdelarna är att brandgasventilatorer

- kan försena tidpunkt då sprinkler sätts igång och således orsaka större bränder tack vare minskning av temperatur under tak,
- kan bidra till ökad antal sprinkler tack vare ovan beskriven mekanism,
- kan släppa igenom otillräckligt ventilationsflöde tack vare minskad bouayncy och brandtryck och kan bli kostnadssätt inte effektivt.

Det finns både studier som bevisar ovan nämnda påstående och som ifrågasätter dem.

I denna studie ett försök med en omvänd analys var gjord. Brandventilators effektivitet i sprinklade anläggningar sätts i fokus här. I det här avseendet är uppskattning av avkylningseffekt på rums temperatur vid sprinkler i drift verkar vara avgörande. De lägre resulterande temperaturerna inom anläggning orsakar mindre brandtryck p g a expansion och mindre bouayncy p g a minskad temperaturskillnad mellan brandgaslager och det fria. Det finns ett antal undersökningar av en fungerande sprinkler med varierande kapacitet samt kartlistning av resulterade parametrar. I dessa undersökningar en rad empiriska ekvationer presenteras. Alperts ekvation som beskriver resulterande temperaturskillnad mellan brandgaslager och inneluft är begränsad till en konstant brand.

Ett fenomen med omvänd flödesriktning via brandgasventilatorer orsakad av lägre inre temperaturer (som är resultat av avkylning med sprinkler) än ute temperaturer är även av intresse för den här studien.

Ett sätt att använda en modifierad och uppåtriktad sprinkler för att öka utflödet genom en brandgasventilator undersöks i studiet. Problemet med uppåtriktad sprinkler är att luftflödet kommer att avstanna på en viss höjd över sprinkler på grund av tyngdkraften. Vattendroppar från sprinkler kommer också att falla ner mot sprinklers huvud genom det uppåtgående luftströmmen. Hur detta skall återspeglas i utflöde genom en brandventilator presenteras i rapporten.

Möjlighet att kunna utnyttja vanliga ventilationssystem för att evakuera bort brandgaser har också studerats i analysen. Ventilationssystemets förmåga att transportera bort brandgaser med förhöjda temperaturer kan också begränsas av hur uthålliga själva ventilationsinstallationer är. En sammanställning och analys av detta problem är gjort i rapporten. De mest karakteristiska parametrarna för olika delar av motorer, såsom startanordningar, lager, remdrift m m presenteras här. Termisk uthållighet av motorer studeras med hjälp av tre modeller:

- med konstant massflöde,
- med konstant volymflöde och
- med konstant tryckfall.

Analys för ett fall med ett konstant massflöde genom fläkt innebär överskattning av massflöde från brandrummet, eftersom fördubbling av temperaturen medför en halvering av densiteten och fördubbling av hastigheten.

Konstant volymflöde innebär en underskattning av massflöde från brandrummet, eftersom fördubbling av temperaturen medför en halvering av densiteten och därmed också massflödet.

Konstant tryckfall utgår från att produkten ρv^2 är lika i normal drift och brand drift. Detta fall motsvarar ett frånluftsventilationssystem med sugkammare till vilken alla ventilationskanaler är anslutna.

Fläktens temperaturberoende effektbehov diskuteras för oreglerad, tryckreglerad och flödesreglerad fläkt.

Motors statiska och dynamiska temperaturuthållighet analyseras med hjälp av en modell.

Några slutsatser från laborationsundersökning av motors temperaturuthålligheten från tre labbförsök diskuteras i rapporten.

Ett sätt att förbättra brandgasevakueringen genom termiska brandventilatorer är att skapa ett övertryck i byggnaden. Detta kan ske genom att köra enbart tilluftsystemet om det är deplacerande och inte omblandande, eftersom röken annars sprids ner till golvnivå.

Ett ventilationssystem kan utformas för att även kunna användas för brandventilation. En enkel åtgärd är att välja frånluftsfläktar som tål en högre temperatur än normalt. Möjligheter att forcera fläktar under kortare tid är också en möjlig åtgärd.

Ett alternativ kan vara att sätta in särskilda brandgasfläktar eftersom ventilationsaggregatets frånluftsdel har vissa strömningsmotstånd i form av filter och återvinningsbatterier och att det normala flödet är för litet.

En tredje metod kan vara att utnyttja även tilluftkanalsystemet för brandgasventilation. Detta kan gå bra för system med omblandande ventilation men passar inte för deplacerande ventilation med lågt placerade tilluftsdon. De båda kanalsystemen för tilluft och frånluft kopplas samman till en eller flera brandgasfläktar. På detta sätt borde det nya ventilationsflödet kunna bli grovt två gånger större än det normala ventilationsflödet.

Det borde också vara möjligt att öka flödet till tre gånger det normala flödet genom att välja en lämplig brandgasventilationsfläkt. Detta innebär att i en lokal med normalt 2 omsättningar/h så kan hela rumsvolymen ventileras ut på 10 min. Ventilationskanalsystemen kan också göras något större än vad som krävs för den normala driften.

Alla de ovan beskrivna lösningar har testats i rapporten. Komplettering av ordinarie ventilationsfläktar i drift, fungerande brandgasfläktar med öppningen av brandgasventilatorer under olika klimatiska förutsättningar presenteras här. Alla dessa åtgärder tillämpade på en dimensionerande anläggning under vissa dimensionerande klimatiska parametrar har testats och redovisats i rapporten. Resultatet bidrar till längre utrymningstider, för att brandgaslagret sjunker långsammare på grund av att brandgasevakueringen förbättras och till att minimera korrosionsskador på dyrbar utrustning.

Resultat från simuleringar får man som numeriska värden för flöde och tryck samt tecken på flödesriktning via en öppning. Detta ger större möjligheter för ytterligare fördjupade och med detaljerade analys av tryck/flödesförhållande i konkreta studerade utrymme.

Problemet som undersöks i denna rapport verkar komplicerad och antaganden, gjorda med viss kunskapsbrist och brist av empiriska data, kan inte minska osäkerheten av resultat. Resultaten kan, alltså, inte tolkas som en slags generell rekommendation för uteslutning av omvänt flöde genom brandventilatorer eller som en generell lösning, utan skall betraktas som en hjälp vid analyser inom detta område.

I den här studien en metod och en modell har skapats, testats och presenterats för att kunna optimera de bästa möjliga lösningar angående brandgasevakueringsåtgärder i deras helhet integrerade med an viss klimatdata.

1   Introduction

The problem of smoke evacuating from large places and buildings has been studied in different ways. Diverse studies on fire hazards have shown that the predominant cause of hazard is smoke, not the temperatures. A primary goal of all smoke removal measurements is to facilitate safe egress in the event of fire. Handling of smoke is also important for fire fighting operations and in surviving property in the event of fire. Nowadays, the costs of the industrial equipment sensitive to smoke and soot are usually even higher then the cost of the building itself. Thus, the control and removal of smoke and fire gases from the building is a vital component in any fire protection schemes. Smoke control and smoke management are two major ways dealing with the problem. In cases with large volume spaces the problem is focused on physical separation of fire and smoke from occupants within the same compartment, maintaining tenable conditions to leave the building safely and reducing damage of contents, and facilitating fire fighting operations after the threat to occupants has been eliminated. However, the possibility of using the ordinary ventilation systems for this purpose during fire progression has not been studied enough and it is just beginning to take a proper place as a fire protection tool. Smoke ventilation interconnected with the use of ordinary ventilation systems is the major point of this study.

1.1   Background

According to building regulations and codes in different countries fire smoke evacuation from large spaces can be achieved by providing buildings with roof mounted smoke and heat openings, which are opened by fusible links and also automatically after detecting fire with the help of different types of detectors, as well as by exhausting smoke with roof mounted fans. In Sweden, both types of smoke venting are recommended depending on the fire class of the space. Additional mechanical exhaust ventilation of the fire volume, providing from four to six air changes per

hour, is also recommended. This rate of air expects to remove smoke approximately the same rate as it is produced. This system is expected to maintain the interface between the smoke layer and the breathing zone sufficiently high above floor level for people to leave the space. Makeup air can be introduced mechanically or in natural way due to the under-pressure in the compartment.

1.2   Some statistics on industrial fires

All statistics on the industrial fires in Sweden is based on the annual reports from the Swedish Insurance Union. There is some uncertainty in the reported values because of the long time of the fire investigation. During all 1980's compensatory fire damages have been increasing and reached 3,7 billion SEK in 1990. In the early 1990's, on the contrary, diminishing of these damages was typical. From the beginning of 1996 up to now the trend have changed once again and 1996 reported 30% total compensatory fire damages increasing in comparison with 1995, while 1997 reported 13% total compensatory fire damages increasing in comparison to 1996's reports. In general, about 70% of the total fire damages reported are fire damages as a result of fires in industrial and trade buildings. Large damages provide between 1 and 2% of the total number of damages, while they are responsible for nearly 40-50% of the total costs. Lowest limit of large damage counted has been also changed from 800 million SEK in 1986, through 1 billion SEK in 1991, and up to 1,5 billion SEK in 1997. The total compensatory fire damages for 10 largest industrial fires in 1994-1996 and in 1996-1997 respectively can be shown in the Table 1.1.

Table 1.1   Total compensatory fire damages for 10 largest industrial fires in 1994-1996 and in 1996-1997 respectively. [Brand&Räddning N 6-7/97, N 6-7/98]

N	Year	Total compensatory fire damages, MSEK
1	1994-1996	469
2	1996-1997	468

A very interesting study of hidden costs in addition to compensatory fire damages made by ABB-concern is presented in Brand&Räddning NR 7 1999. The ABB-concern studied how much (besides costs covered by insurance) have 19 concern's different companies paid itself in order to repair damages caused by different fires. They called these costs "hidden costs". According to the results reported these hidden costs could axceede up to 20-50% of company's annual turnover.

Table 1.2   Results from the study of total and hidden compensatory fire damages in 8 largest companies. [Brand&Räddning NR 7 1999]

Company Nr	Annual turnover,	Hidden Costs,	Total insurance compensation,	Hidden Costs, % of the annual turnover,	Hidden Costs, % of the total insurance compensation,
	MSEK	MSEK	MSEK		
1	2270	900	1400	40	64
2	1100	450	1800	41	25
3	780	350	1600	45	22
4	550	250	625	46	40
5	950	210	700	22	30
6	900	190	460	21	41
7	310	170	420	55	40
8	250	100	340	40	29

As the Table 1.2 shows, even the best insurance can not cover all damage costs caused by the industrial fire. Hence, the real total compensatory fire damages can be 1.2 – 1.65 times higher then those reported.

The problems that are common to all large volume spaces are: type of fuel, quantity of fuel, arrangement of the fuel package, effectiveness of the fire sprinkler system, and ability to provide safe and timely egress.

2   Study of the literature

In order to determine the current state of knowledge regarding smoke removal from the large spaces by all special measures along with using ordinary ventilation systems, the following study was made. The state of knowledge and research publications in this regard have been searched through different databases in science and technology and via several search programs in Internet. In addition, current publications on this matter in different scientific and technical periodicals were followed. As the study is interdisciplinary in nature and comprises different fields of engineering knowledge such as fire protection engineering, building services and building science, publications within both the fire protection and building science periodicals have been followed. The following survey is written as a summary of different literature sources.

2.1   Databases

All in all seven major databases were searched through twice with a one-year interval. These databases are as follows:

- IBSEDEX,   which covers all aspects of building services world-wide, published since 1960. It includes information on technical books, reports, conference papers, journal articles and standards,

- ICONDA,   which covers the world-wide literature on all fields of building construction and design, energy conservation, civil and structural engineering, architecture and town planning, published since 1976. Sources of information are technical books, conference papers and journal articles,

- COMPENDEX, which is a comprehensive interdisciplinary engineering database, covering different areas of engineering, civil, energy, mechanical, environmental, etc. Sources of information are technical reports, conference papers and proceedings, published since 1970,
- NTIS, (National Technical Information Service), which is a multidisciplinary bibliographic database. The sources are publications, especially unrestricted reports, on research, development and engineering projects, sponsored by US and non-US governments from 1964 to the present,
- PASCAL, which is a multilingual, multidisciplinary, bibliographic data base covering the core of world literature in Science, Technology and Medicine. Computerised since 1973, the PASCAL database now includes over 11 million references,
- AIRBASE, which is the Bibliographic Database of the International Energy Agency's Air Infiltration and Ventilation Centre. It contains abstracts of articles and publications relating to energy efficient ventilation and includes topics on ventilation strategies, design and retrofit methods, calculation techniques, standards and regulations, measurement methods, indoor air quality and energy implications. Entries are based on articles and reports published in journals, internal publications and research reports.

The information search showed that there are many articles on this issue treating the problem of fire smoke evacuation from large spaces in general. Some of these are comparatively old, from the 60s and early 70s, which makes them nearly unobtainable.

Although much of the information presented concerns atria, it actually applies to any large volume space, including convention centers and covered malls.

3   History

A series of fires in high-rise buildings in 1960's in different countries in Europe and in USA waked up attention to the problem associated with smoke in them. Since then it has been widely acknowledged that handling of smoke is extremely important in surviving lives and property in the event of fire. As modern building designs evolved, fire smoke evacuation became increasingly complicated, and became larger and larger factor in the design of ventilation systems in buildings. At the same time running ordinary ventilation systems role as a fire smoke-evacuating tool in case of fires in different types of buildings increased.

Originally, the most common way of smoke venting during fires was a natural venting through windows broken at high temperatures. This was totally uncontrolled and unpredictable way of smoke venting. Besides that, the fire itself in the space must be large enough and hot enough to cause collapse of the glass. Such smoke venting systems seem to be insufficient in protecting of large buildings with substantial areas distant from windows. Such buildings were provided with roof mounted smoke and heat openings (so called smoke vents), which would be opened by fusible links and also automatically after detecting fire with the help of different types of detectors. Another type of smoke venting is exhausting smoke with roof-mounted fans. In Sweden, the both types of smoke venting are recommended depending on fire class of the space. Sprinklers, which are widely used in industrial and storage spaces could also affect detecting and, hence, smoke venting. Handling of smoke in buildings can be made with the help of smoke control and smoke management systems.

3.1 Smoke control and smoke management systems

One should differ between the smoke control and smoke management systems. Although, they share a primary goal of facilitating safe egress in the event of fire, there are essential differences between them:

- Smoke control system is an engineered system using fans providing pressure differences and air flows in order to limit smoke movement across barriers,
- Smoke management system is an engineered system using different methods in order to modify or drive smoke movement singly or in combination.

Besides this, fire fighting operations and reduce loss of property should be facilitated.

3.1.1 Smoke control system

Smoke control system comprises all kinds of measures providing compartmentation and exclusion of smoke and heat from selected compartments comprising the route of egress, or imprisonment of smoke in the compartment of origin along with maintaining tenable conditions in the surrounding spaces. This is done by exhausting smoke from the fire compartment while supplying air to the surrounding compartments. Such measures are not intended to maintain or restore tenable conditions within the compartment of fire origin. It is considered that reducing of initial smoke density to such extent that it makes an exit sight visible during some ten or fifteen minutes to be sufficient. Complexity of smoke control systems varies a lot evolving relatively simple systems replacing air via broken windows and roof vents and more complicated systems excluding smoke from all places except for fire compartment and even pressurisation of certain places (stairwells). The aim of all measures is to separate smoke from other places excluding fire origin place, i.e. to keep smoke and occupants in a different enclosed volumes, thus providing tenable conditions for the egress and for use as a base for fire fighting operations. At the same time it means that the compartment of fire origin can be filled with smoke and so far, untenable.

3.1.2 Smoke management system

The main goals of smoke management in large volume spaces is to physically separate fire and smoke from occupants within the same compartment, maintaining tenable conditions to leave the building safely and reducing damage of contents, and to facilitate fire fighting operations after the threat to occupants had been eliminated. The purpose with the smoke management is to create a smoke layer above the occupied level. Figure 3.1 shows the main principal of the smoke management system.
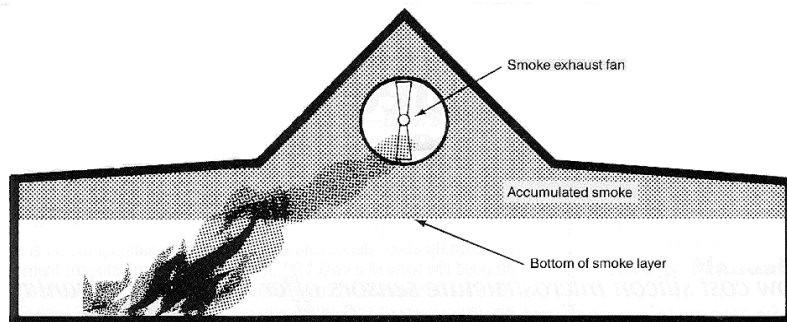
Figure 3.1   The smoke exhaust system in large spaces allows smoke to accumulate up high, keeping occupied level clear from egress [Kenneth M. Elovitz, P.E; David M. Elovitz, P.E. 1993].

According to building regulations and codes in different countries including Sweden this can be achieved by providing buildings with roof mounted smoke and heat openings, which are opened by fusible links and also automatically after detecting fire with the help of different types of detectors, as well as by exhausting smoke with roof mounted fans.

According to the building regulations and codes in USA (BOCA 1987) additional mechanical exhaust ventilation of the fire volume, providing from four to six air changes per hour is recommended. This rate of air expects to remove approximately the same rate as smoke produced. This system is expected to maintain the interface between the smoke layer and the breathing zone sufficiently high above floor level for people to leave the space. Makeup air can be introduced mechanically or in natural way due to under-pressure in the compartment. This measure is regarded to be questionable and insufficient.

The problem with smoke management is rather complex and there are an amount of problems to be solved. Some of the problems are:

- The combination of internal contra external pressures in the space can result in reversed/"wrong" flow direction through the smoke vents. Internal pressure can be less then external pressure on the roof thus forcing outdoor air flow into the space instead of smoke evacuating.
- The velocity of makeup air has been estimated to be in order of 1 m/s. Velocities higher than that may cause drawing down smoke from the smoke layer by induction and mixing it with the ambient air. A makeup air jet with the velocity of approximately 1 m/s can cause drawing of smoke out of a smoke layer above and mixing it throughout the space.
- "Plugging" effect of a roof mounted smoke exhaust fan which cause clear air from below the smoke layer to be drawn up through the smoke layer and into exhaust. This can induce smoke from the bottom of the layer down in the occupied level and mixing it throughout the space.
- The required air change rate of 6 /h seems to be questionable (incapable) parameter (large for large volumes and little for the little ones).
- Smoke stratification can be a problem because smoke may not reach ceiling-mounted detectors. During the summer a hot layer of air can form under the large volume space ceiling (especially in the case with the old ceilings without sufficient insulation). Under certain conditions a smoke plume may not have sufficient buoyancy to penetrate such a hot air layer due also to the fact that temperature in the plume decreases with height.
- A sprinkler system installed in many of studied places is a common measure suppressing fires. This system effects the smoke layer cooling it and driving it to the floor (by the water momentum), thus effecting both the buoyancy and smoke management measures. The height of the buildings makes effectiveness of fire sprinkler protection questionable. Because of delayed response, sprinklers may not be effective in suppressing fires in spaces with ceiling heights greater than 11 to 15 m (Degenkolb 1975, 1983) or in controlling fires in atria exceeding 20 m in height (Tamura 1995). Smoke temperatures after been evaporatively cooled by sprinkler spray can be sometimes even below ambient temperatures (Lui 1977). In this connection the problem of strong negative response from people been immersed in any smoke regardless of its tolerable properties can be discussed.

- Localised geometric irregularities disturb the airflow and create local zones of turbulence, which result in unexpected smoke movements and mixing. Smoke discharging from the smoke exhaust fan can re-appear through makeup air, smoke at dead spots with no source of makeup air.
- In some high spaces, the smoke layer can even be allowed to grow down towards the floor as long as the smoke will not reach the occupied level in less time than people need to leave the space. Such level can vary according to different sources.

4   Design fire

The starting point for smoke management system is determining of the fire size. The great variety of possible fire scenarios in such spaces leads to the necessity to describe the fire progress in more general terms.

$$Q(t) = \alpha\, t^{n} \qquad\qquad\qquad\qquad \text{W} \qquad\qquad (4.1)$$

where Q is in W and t is in seconds, α is in W/s^{n} and is specific for a certain fire progress. The fire can be generally considered a steady, n=0, or an unsteady fire, n >0. An unsteady fire is the fire that varies with respect to time. A steady fire has a constant heat release rate as a result of limitations of fuel and combustion air. The real fire is unsteady in its nature, but the steady fire is a useful idealisation in many cases. In the absence of specific heat release rate data it is recommended to assume a steady fire. This will result in a more conservative consequence than using an unsteady fire. An average heat release rate for the design fuel area could be estimated.

Design based on unsteady fire results in lower ventilation rates then in case with steady fire. Large spaces are usually not restricted by lack of combustion air. In spite of this fact the steady fire can be assumed for the present study. So, the designed steady fire design results in somehow overestimated flows that are on the safe side.

Vast variations in heat release rates of fires in large spaces leads to certain assumptions of the designed fire size.

There are some assumptions for typical spaces protected by sprinklers in different sources. In BOCA and ICBO recommends 4640 kW (after been conversed from BTU units) for mercantile, storage and industrial occupancies. In each case, the assumed fire size is 9.3 m^{2}, which is a reasonable assumption for typical spaces protected by automatic sprinklers. This design fire is similar to recommend by Klote and Mike: 5 MW, 1992. In some sources fires as large as 25 MW have been discussed.

The initial period of time for the fire to reach the steady heat release rate can be questioned for different fires and spaces. Fast t-squared growth up to steady fire of 2 MW, 5 MW and 25 MW is shown in the Figure 4.1.

Time (min)

Heat Release Rate (MW)

Time (s)
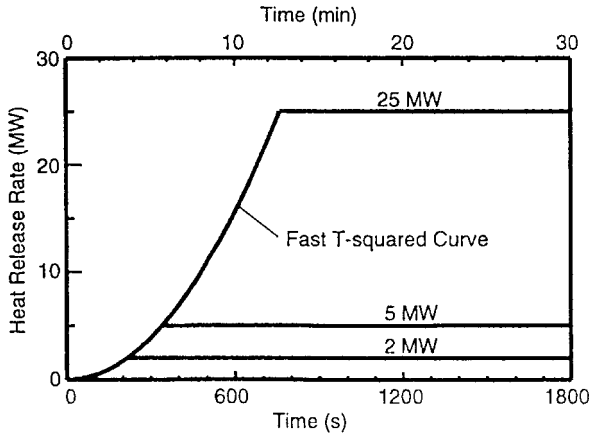
Figure 4.1.   *Fire growth for fast t-squared fires up to steady fire of 2 MW, 5 MW and 25 MW [John H. Klote, 1997].*

"T-squared" fires are classed after α by speed of growth, as ultra-fast, fast, medium and slow, based on the time to reach a heat release rate of 1 MW. For the purpose of this study a steady fires of 2.5 MW, 5 MW and 25 MW are chosen.

5　Smoke filling concept

Here, the discussions on smoke filling will be concentrated on the simpler problems. The concept of a smoke filling a space with a smoke vent and smoke inlet is shown in Figure 5.1.
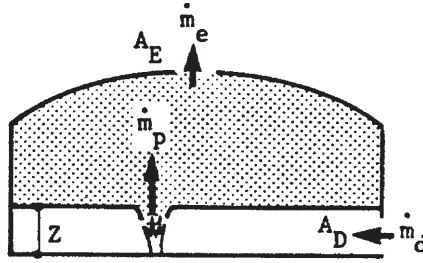
Figure 5.1　　*The conceptual diagram of smoke filling with a vent at the top and an opening on the wall side [Takeyoshi Tanaka, Toshio Yamana, 1985].*

Both the smoke layer density ρ_s and horizontal section area of the space A and level of smoke are constant, and the fire is steady.

The simple mass balance equation yields

$$\dot{m}_d = \dot{m}_p = \dot{m}_e = \dot{m} \tag{5.1}$$

where

$\dot{m}_d$　　　mass flow through an opening, kg/s;

$\dot{m}_p$　　　mass flow of a fire plume, kg/s;

$\dot{m}_e$　　　mass flow through a vent, kg/s.

The temperature elevation of the interior surfaces that can contact with the smoke layer is neglected.

Takeyoshi Tanaka, Toshio Yamana's, 1985 equation for the mass fire flow is

$$\overset{\bullet}{m} = c_m \left(\frac{\rho_a^2 \, g}{c_p \, T_a} \right)^{1/3} Q^{1/3} \, z^{5/3} \tag{5.2}$$

where

$\overset{\bullet}{m}$ mass fire flow, kg/s;
Q heat release rate of fire, kW;
z   height of smoke layer above the fire, m;
T_a air temperature, K;
ρ_a air density, kg/m^3;
g acceleration due to gravity, m/s^2;
c_m = 0.21; and
c_p specific heat of gas, kJ/kg K.

And after substituting of ρ_a, g, c_m, c_p and T_a =293K

$$\overset{\bullet}{m} = 0.0765 \, Q^{1/3} \, Z^{5/3} \tag{5.3}$$

The heat balance

$$Q = c_p \, \overset{\bullet}{m}_s \, (T_s - T_a) + h \, A_w \, (T_s - T_a) \tag{5.4}$$

where

Q heat release rate of fire, kW;
T_a air temperature, K;
T_s smoke layer temperature, K;
h heat transfer coefficient, kW/m^{2}K;
A_w area of the interior surface that contacts with smoke layer, m^2.

Thus, smoke layer temperature

$$T_s = T_a + \frac{Q}{c_p \, \overset{\bullet}{m}_s + h \, A_w} \tag{5.5}$$

Takeyoshi Tanaka, Toshio Yamana, 1985 proposed a trial and error method based on the above-mentioned equations 5.2 - 5.5 for figuring out mass fire flow and temperature of the smoke layer.

Toshio Yamana and Takeyoshi Tanaka, 1985 made experiments with steady fire with the heat release rate of 1.3 MW in a large space with floor area of 720 m^2 and 26.3 m height. Different types of venting were tested. Experiments comprised

- natural smoke filling of the space,
- natural smoke venting through openings on the upper part of the wall,
- mechanical venting with exhaust flow of 6.0 m^3/s (1.1 1/h), 4.5 m^3/s (0.85 1/h) and 3.2 m^3/s (0.6 1/h) respectively; and
- lower part pressurisation with air supply rate of 20.4 m^3/s (3.8 1/h) and 23.4 m^3/s (4.45 1/h) respectively.

Comparison between test results and results predicted by the above-mentioned simple model showed comparatively good agreement. Unfortunately, conclusions regarding effectiveness of tested smoke control/management systems could not been drawn due to initial air venting data inequality.

Some of the mass flows calculated according to above mentioned simple method for the steady fires with heat release rate of 2.5 MW, 5 MW and 25 MW respectively are shown in the following Table 5.1.

Table 5.1.   Mass flows for the steady fires with heat release rate of 25, 5 and 2.5 MW respectively.

Smoke layer height Z, m	Mass flow m, kg/s Heat release rate, MW		
	2.5	5.0	25.0
1	1.0	1.3	2.2
2	3.3	4.1	7.1
4	10.4	13.1	22.5
6	20.5	25.8	44.2
8	33.1	41.7	71.3
10	48.1	60.5	103.4

According to the equation 5.5, smoke layer temperature T_s depends strongly on the area of the interior surface that contacts with smoke layer A_w. For the fire in a space of a certain area the temperature depends on the smoke layer level above the floor. For unsprinklered fires the products of combustion are commonly in the range of 1200 K (Kenneth M. Elovitz, David M. Elovitz, 1993) while for sprinklered fires temperature of 351 K is commonly used (BOCA, 1993).

Heskestad's (1984) equation for the mass flow is

$$\dot{m} = c_1 \, Q_C^{1/3} \, (z - z_0)^{5/3} \, [1 + c_2 \, Q_C^{2/3} \, (z - z_0)^{-5/3}] \qquad (5.6)$$

where

$\dot{m}$ mass flow in plume at height z, kg/s;

Q_c convective heat release rate of fire, kW;

z height above top of fuel or height of the first indication of smoke above the fire, m;

z_o virtual origin of the plume, m;

c_1 =0.071; and

c_2 =0.026.

According to John H. Klote's (1997), the commonly used virtual origin correction of the plume equations are not needed for large spaces smoke management, so the deviations of fire plume mass flow due to omitting the virtual origin correction can be neglected (Figure 5.2).
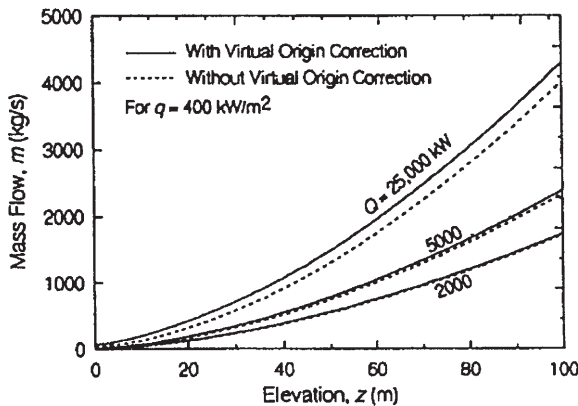
Figure 5.2   *Mass flow production with and without correction for virtual origin for q=400 kW/m² [John H. Klote, 1997].*

Hence, equation 5.1 becomes

$$\dot{m} = c_1 Q_C^{1/3} (z - z_0)^{5/3} + c_8 Q_C \tag{5.7}$$

where

c_1 =0.071; and
c_8 =0.0018.

So, after substituting coefficients and z_0=0

$$\dot{m} = 0.071 Q_C^{1/3} z^{5/3} + 0.00185 Q_C \tag{5.8}$$

Comparison between equations 5.3 and 5.8 shows, that result is nearly the same with the assumption that in the equation 5.7 Q_c=Q. The last assumption can be questioned as the convective part of the total heat release rate can vary between 50 and 70% with the resulting mass flow fault of 3 and 4% respectively.

A simple picture of a building filled with smoke with a vent in the roof is shown in the Figure 5.3.
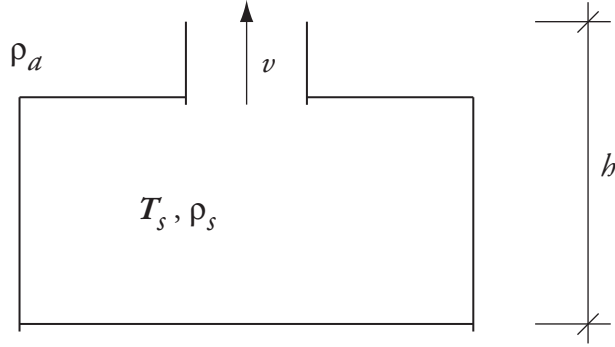
Figure 5.3   Building filled with smoke with a vent in the roof.

Pressure balance in this case yields

$$(\rho_a - \rho_s) g h = \rho_s v^2 / 2 \tag{5.9}$$

$$v = \left[\frac{2 (\rho_a - \rho_s) g h}{\rho_s} \right]^{0.5} \tag{5.10}$$

where

ρ_a air density, kg/m^3;
ρ_s smoke density, kg/m^3;
g acceleration due to gravity, m/s^2;
h height above the floor, m and
v velocity, m/s.

Hence, mass flow

$$\dot{m} = \rho_s \, v \, A = \left[2 \left(\rho_a - \rho_s \right) \rho_s \, g \, h \, A^2 \right]^{0.5} \qquad (5.11)$$

where

$\dot{m}$ mass flow, kg/s;
A area of the outlet, m^2

Mass fire flow increases along with increased smoke layer temperature, T_S, but only if $T_S < 2 \, T_a$, and decreases along with decreasing increased smoke layer temperature, T_S, but only if $T_S > 2 \, T_a$. This is illustrated in the Figure 5.4. Meanwhile, volumetrical fire flow increases along with increased smoke layer temperature, T_S.
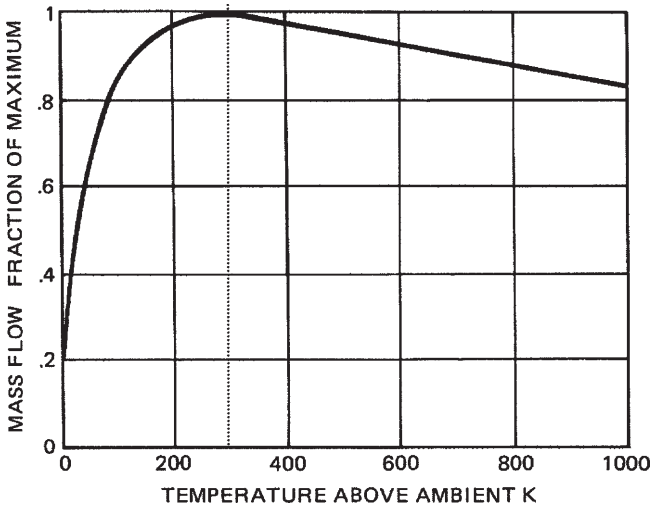
Figure 5.4   Mass flow fraction of maximum as a function of smoke temperature above ambient (SFPE 1995).

The above-presented equations for mass fire smoke flow evaluating are very simplified and are based only on the fire itself. They pay no attention to other parameters/factors influencing the studied spaces. The study of resulted fire smoke flow out from the building through different vents is presented further in Chapters 10-14.

6   Some statistics on roof mounted smoke vents function

As it was described earlier, one of the common ways of smoke evacuation is providing building with roof mounted smoke openings/vents, which would be opened by fusible links and also automatically after detecting fire. There are several different types of smoke vents:

- With outwards opened two sheets (usually made of steel)
- With outwards opened one sheet (usually made of tree with the lid of steel or acrylic)
- With downwards opened single hatch (usually made of tree with the hatch of steel or acrylic)
- Facade shutters (installed in facades with steel frame glass particles).

There can be mentioned several different types of opening devices:

- Melting type (opens automatically at high temperatures),
- Combined melting type and magnetic type (can opens both automatically at high temperatures and manual from the ground level),
- Combined melting type and wire (can opens both automatically at high temperatures and manual from the ground level).

Almost all the types could be furnished with a handle for outdoor operation.

The reliability of such smoke vents has been discussed in the branch. Some study on the smoke vents function is made. With the permission of Carl-Gunnar Jacobsson from BV-Service, certificate service of fire

smoke vents, Landskrona, Sweden, the following results of the natural smoke vents function analyses are presented in the Table 6.1. The service control of smoke vents was made in 1995-1998.

Table 6.1   Results from the natural smoke vents function study.

Company	Total amount of controlled smoke vents	Amount of opened smoke vents	In % of total amount of vents
Åkerlund and Rausing Group, Lund	414-428	379-388	91-93
Alfa-Laval AB, Lund	107	80	75
Barsebäck nuclear power station, Barsebäck	75	50	67

As the Table 6.1 shows, the amount of roof mounted smoke vents that did not opened during the control can reach up to 33% of the total amount of them.

The usual cause of the smoke vents not opening are as following:

- a melting hatch is replaced with a wire,
- weak opening device springs,
- inertia in moving parts of an opening device,
- a fixed lock (e.g. tapped when painted),
- wrong steel fittings placement,
- handles for outside operation have got rusty,
- swallowed frame tree locks,
- wrong done reparations,
- opening springs have been taken down,
- transport safety devices have not been taken down after delivery,
- wrong installation (e.g. wrong size),
- pipes, ventilation systems network, cables, etc. placed directly under the downward opened smoke vents.

Many faults depend on the following:

- fire staffs lack of knowledge,
- insufficient control and maintenance,
- wrong made control (e.g. only manual device control without automatic function control).

Furthermore, there is lack of rules on how often the smoke vents should be controlled. The only one existing recommendation in Sweden yields, that 1/6 of all smoke ventilators should be controlled every sixths month (i.e. all the smoke vents should be controlled in a three-year period). In reality, control routine can very from the each year control to no control at all during the lifetime. There are cases reported with no smoke vents control or maintenance during 20-25 years.

7   Case study

In order to gather some data on smoke venting systems in existing large industrial buildings an attempt was made to contact some of the industries in the Southern Sweden. Unfortunately, due to objective reasons it failed. The only one industry that the author was able to visit was Åkerlund&Rausing Group in Lund.

Åkerlund &Rausing Group, Lund

Ventilation system in all storage and workshops is of the supply-exhaust type. Supply ventilation is of both mixing-type and displacement type while exhaust ventilation is of local type with different hooks both stationary and built into the process equipment. All the ventilation systems are VAV (variable are volume) systems and are regulated after out- and indoor temperatures as well as after the technological process required air volume. Circulation air is also used in the ventilation systems. Exhaust air from some of the workshops is cleaned before it is used as a circulation (return) air or before it is thrown out.

Workshops are sprinkled, there are smoke detectors in all spaces and natural ventilators with both manual and melting type of opening for smoke evacuation. The total area of the natural ventilators is 2% of the protected floor area.

8 Factors effecting building in case of fire

Smoke management can be interpreted as a successful smoke venting from space effected by different factors in the fire case. These factors are:

- wind pressure around the whole building (the roof included),
- buoyancy due to temperature difference,
- fire thermal volume expansion,
- ventilation pressure,
- sprinklers.

Resulting buildings internal pressure is a function of all these factors.

Combination of wind pressure on building and airtightness of the building along with opening of doors, windows in the walls and smoke vents on the roof can result in great variations of pressure. Different openings can be opened at the windward and leeward sides of building and roof at the same time. In order to evaluate indoor pressure under different circumstances the following study was done.

The flow direction through any leakage or opening is determined by the pressure difference between outside and inside. The wind creates both over and under pressure on the surfaces that is relative to the normal pressure far off the building. The internal pressure is not equal to this normal pressure but mostly somewhat less. This internal under pressure occurs for a building with even leakage distribution and due to the fact that most of the surfaces have negative wind factor and thereby under pressure. The only surfaces with the over pressure are those exposed to direct wind attack. This means for a cubic building that only one side will have over pressure if the wind is perpendicular to that side. The other four surfaces (roof included) all have under pressure.

8.1 Wind pressure on the roof, form factors

For large roof areas the wind can reattach to the roof downstream from the cavity and thus reverse the airflow in the ordinary cases. Streamline patterns are independent of the wind speed and depend mainly on the shape of the building and upwind conditions. The distance of approximately 1.5 buildings scaling length R (m) above the roof level influences the flow. The roof pitch begins to affect flow when it exceeds about 15°; at 20° the flow remains attached to the upwind pitched roof and produces a re-circulation region downwind from the roof ridge. In addition to the flow patterns, the turbulence of the approaching and the unsteady character of the flows cause surface pressures to fluctuate. It is usual to discuss the time-average values (the average period is about 600 s).

The peak wind pressures can be two-three times higher then the average ones:

$$p = \mu \times 0.5 \rho v^2 \tag{8.1}$$

where

p the local wind pressure, Pa,
μ the building surface local wind pressure coefficient, -,
ρ the outdoor air density, kg/m^3,
     (ρ=1.25 kg/m^3 at ambient temperature of 10°C and ocean level),
v approach wind speed at the upward height, m/s.

Values of the local wind pressure coefficient μ generally depend on the buildings shape, wind direction, the influence of the nearby structures, vegetation, and terrain features. In order to calculate wind pressures due to different conditions characteristically for the particular place one uses v_{ref} instead of v in (8.1). Other factors effecting wind pressure are the height of the building, the height over the ground and terrain features. The resulting equation is

$$p = \mu \times p_c \tag{8.2}$$

where
p_c the characteristic wind pressure, Pa.

Particular surface pressures on the roof of a low-rise building depend strongly on the roof slope. For the very low slopes the pressure is negative on the whole roof. For steeper slopes (> 20°), the pressures are positive on the windward slope depending on roof slope, slope angle and wind direction. For certain parts of the roof μ can reach the following top values:

- for gable, pentroof and hipped roofs - 1.0,
- for butterfly roof - 0.2,
- for arched roof - 0.6.

Assuming a building of four, eight and ten meters height built in the terrain type II and substituting q_c from the Bilaga C I "Snö och vindlast" in the (8.2) for different μ values characteristic for Swedish wind cases it results in the values set out below.

Design wind data for the purpose of this study refers to Swedish standard design wind velocity for wind load, and is a mean velocity during 10 minutes at the height of 10 m in the open terrain. This wind velocity exceeds on average once in 50 years.

Table 8.1   Wind pressure on the roof, p_{dyn} (Pa).

μ	Height, (m)	v_{ref} (m/s)					
		21	22	23	24	25	26
0.1	4	45	50	54	59	64	69
	6	45	50	54	59	64	69
	8	59	61	67	73	79	86
	10	59	65	71	77	84	90
0.5	4	225	250	270	295	320	345
	6	225	250	270	295	320	345
	8	280	305	335	365	395	430
	10	324	354	375	385	418	452
1.0	4	450	500	540	590	640	690
	6	450	500	540	590	640	690
	8	560	610	670	730	790	860
	10	590	650	770	836	890	904

As Table 8.1 shows, wind pressure values on the roof can vary between 20 and 900 Pa.

8.2   Smoke layer buoyancy

The difference in pressure between the hot smoke layer and the outside in ceiling level is

$$p_B = \frac{g\,\rho_0\,\Delta T\,d}{T_h} \qquad\qquad (8.3)$$

where

p_B pressure due to buoyancy, Pa,
ρ_o density of the ambient air, kg/m^2,
d depth of layer of smoke, m,
T_h temperature of hot layer, K and
ΔT temperature difference between the hot layer temperature and temperature of ambient air, K.

Assuming a building of four, six, eight and ten meters height filled with smoke and smoke layer temperature varying between 400 and 1200 K and ambient temperature of 293 K results in the values set out below.

Table 8.2   Pressure as the result of buoyancy for the studied space filled with smoke, Pa.

Height, (m)	Smoke layer temperature T_h, K				
	400	600	800	1000	1200
4	13	24	30	33	36
6	19	36	45	50	53
8	25	48	60	67	71
10	31	60	75	83	89

As Table 8.2 shows pressure difference due to buoyancy varies here between 13 and 89 Pa under the assumption that the whole height of the building is filled with smoke. Maximal pressure due to smoke layer buoyancy can never exceed 12 Pa/m (for the infinite ambient temperature). For the temperature doubled from 300 K to 600 K this pressure is equal to 6 Pa /m.

It is well known that wind pressures applied to whole building can be greater than pressure due to buoyancy in many situations. Comparison between the Table 8.1 and the Table 8.2 illustrates this statement applied

to certain parts of the roof. Pressure due to buoyancy in smoke filled buildings at very high inside temperatures is slightly comparable with the lowest wind pressure values for low slope roofs and the weak wind velocities. Other wind pressure values for other combinations of slope angle and wind speed are incomparably larger then arbitrary values of pressure due to buoyancy. Furthermore, the above-presented case with a building filled with hot smoke is not appropriate for this particular research, as it relates to very violent phase of fire.

8.3 Pressure rise due to expansion

Pressure rise due to expansion can become a determining factor in indoor pressure assessment.

8.3.1 Constant rate of rise of temperature, B (traditional case)

According to The SFPE Handbook, 1995 the pressure rise is related to the mean temperature in the space and the temperature rise by the following equation

$$\Delta p_f = 500 \, (B \, h \, A_c)^2 \, / \, A_l^2 \, T_h^3 \tag{8.4}$$

where

B rate of rise of temperature, K/s;
h height of the space, m;
A_c area of the space, m^2;
A_l area of the openings (including the leakage path), m^2;
T_h smoke layer temperature, K.

According to SFPE 1995 the recommended value of B is equal to 4 K/s.

According to the Swedish Building Codes BBR 94, the permitted leakage counted in leakage path's area (Gordonova P. 1998) should not exceed 2.5 cm^2/m^2. The requirement relates to the area of the building envelope. The building envelope area is defined as the area exposed to the outside air. According to Polina Gordonova (1998), the assumption, that the air leakage according to BBR 94 in the compartments, hotels, offices and hotels can be applied to the whole buildings envelope, inner constructions included, was accepted as a suitable and probable. The same logic can be applied to the industrial buildings (in particular to the old

ones) as data on the airtightness of such spaces is not sufficient and the differences in building codes and construction traditions abroad differ from those in Sweden.

A case with space area of 100 m², height of 10 m and B=4 K/s (SFPE 1995) was studied here. Standard leakage path in this case is equal to ~0.15 m². Larger opening, A$_l$, of 1 m² (half-opened standard door) was also studied. Pressure rise in the assumed space with leakage paths, A$_l$, of 1 m² and 0.15 m² respectively is presented in the Table 8.3. According to Lundin L. I. 1986 "Air leakage in industrial buildings - description of equipment" the air leakage in nine examined industrial buildings in Sweden varied between 2.7 m³/h m² and 10.2 m³/h m² at pressure difference of 75 Pa. This is equivalent to interval of 2.2 m³/h m² and 8.3 m³/h m² at pressure difference of 50 Pa.

Table 8.3   Pressure rise due to expansion during fire as a function of temperature rise, Pa (according to The SFPE Handbook, 1995).

Leakage area, m²	Smoke layer temperature T_h, K				
	400	600	800	1000	1200
0.15	5555	1644	693	356	204
1.0	125	37	15.6	8	4.6

As it is seen from the Table 8.3, pressure rise due to expansion decreases with temperature increasing.

8.3.2   Non-constant rate of rise of temperature, B

As a matter of fact, B (K/s) is not a constant. It also depends on temperature rise that can be shown below

$$B = P / \rho_h \, c_p \, V = P T_h / \rho_o \, T_o \, c_p \, V \qquad (8.5)$$

and

$$\rho_h = \rho_o T_o / T_h \qquad (8.6)$$

The equation 8.4 can be rewritten as follows

$$\varDelta p_f = 500\,(\frac{P\,T_b}{\rho_o\,T_o\,c_p\,V})^2\,V^2\,/\,A_l^2\,T_b^3 = 500\,\frac{P^2}{\rho_o^2\,T_o^2\,c_p^2\,A_l^2\,T_b} \quad (8.7)$$

where

P heat release rate , W;
V volume of the space, m^2;
A_l area of the openings (including the leakage path), m^2;
T_o ambient air temperature, K,
c_p specific heat at constant pressure, J/kg K.

As it is seen from the equation 8.7 pressure rise due to expansion in the space is independent of its volume.

8.3.3   Pressure rise model

A model based on Figure 5.3 was made and a computer program SIMNON was used.

SIMNON is a computer program for the simulation of mathematical, non-linear relationships between the input and output signals in a system, as well as connection of several dynamical subsystems into one total system. Simnon is marked by SSPA Systems, a group within SSPA Maritime Consulting AB.

The model describes heat release rate generally as

$$P_f = P_c + P_l\,t_m + P_q\,t_m^2 \quad\quad\quad\quad\quad\quad (8.8)$$

where

P_f heat release rate, kW;
P_c heat release rate for steady fires, kW;
P_l heat release rate per time unit for linear fire progress, kW/s;
P_q heat release rate per time rise to the second power unit for square fire progress, kW/s^2;
t_m time of fire progress, s;

Mass change

$$dm = -\,A\sqrt{2\,\rho\,\varDelta p}\;\;,\,\text{if p>0} \quad\quad\quad\quad (8.9)$$

$$dm = A\sqrt{-\,2\,\rho\,m_s\,\rho\,/\,V}\;\;,\,\text{if p<0.} \quad\quad (8.10)$$

where

dm	mass flow derivative, kg/s;
A	area of the openings (including the leakage path), m^2;
ρ	density, kg/m^3;
Δp	pressure difference, Pa;
t_m	time of fire progress, s;
V	place volume, m^3;
m_s	start mass, kg

Temperature change is

$$dT = \frac{P_f}{m\,c} \text{, K/s} \tag{8.11}$$

where

dT	temperature derivative, K;
m	mass, kg and
c	specific heat, kWs/kg K.

Pressure rise in the space due to expansion is

$$\Delta p = p_s \left[\frac{m}{m_s} \frac{T}{T_s} - 1 \right] \tag{8.12}$$

where

Δp	pressure rise due to expansion, Pa;
p_s	start (atmospheric) pressure rise, Pa;
T	smoke layer temperature, K and
T_s	start (ambient) temperature, K.

Simulations based on the above-presented model were made for both the steady fires and t^2-fires with heat release rate of 1 MW, 2,5 MW and 5MW respectively in a 1000 m^3 space. The simulations is interrupted when the temperature in the space exceeds 1200 K.

The results of this simulations of temperature rise rate, B, for the steady fires and t^2-fires with heat release rate of 1 MW, 2,5 MW and 5MW respectively is shown in Figures 8.1 and 8.2.
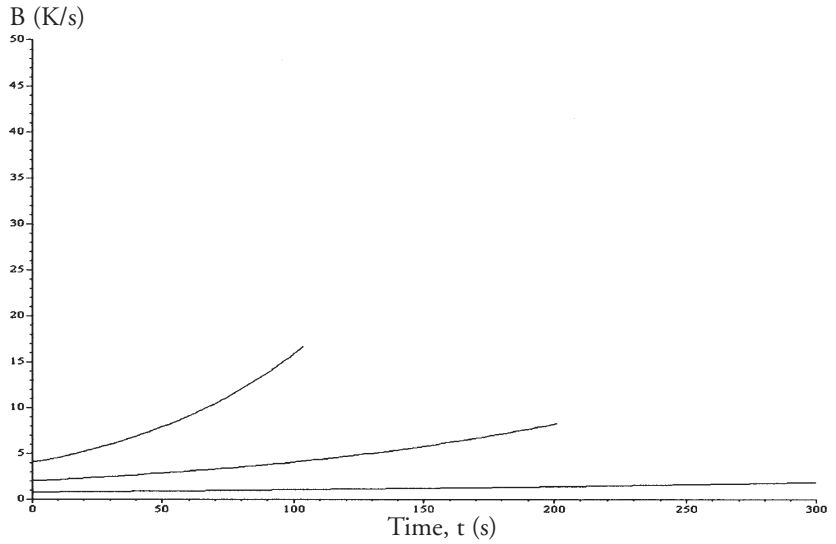
Figure 8.1   Temperature rise rate, B, / time for different steady fires with heat release rate of 5 MW, 2,5 MW and 1 MW respectively counted downwards.
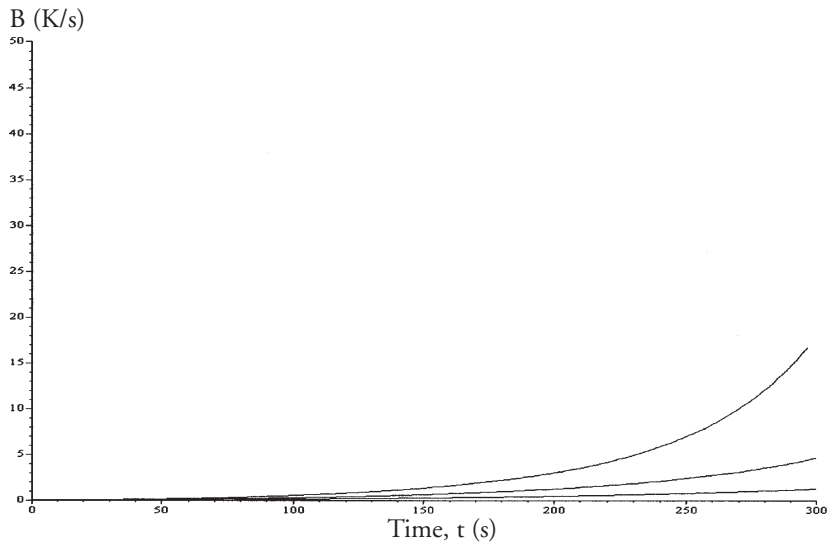
Figure 8.2   Temperature rise rate, B, / time for different t² fires with heat release rate of 5 MW, 2,5 MW and 1 MW respectively at 300 s counted downwards.

As it is seen from Figures 8.1 and 8.2 B exceeds 17 K for both steady and t^2-fires. Velocity of temperature rise rate, as it is expected, is lower for t^2-fires. This observation will be discussed further in the present subchapter in terms of resulted pressure rise due to expansion. The results of simulations of pressure rise for the steady fires with heat release rate of 1 MW, 2,5 MW and 5MW respectively is shown in Figure 8.3 (A_l =0.15 m^2) and Table 8.4 (A_l =0.15 m^2 and A_l =1 m^2).
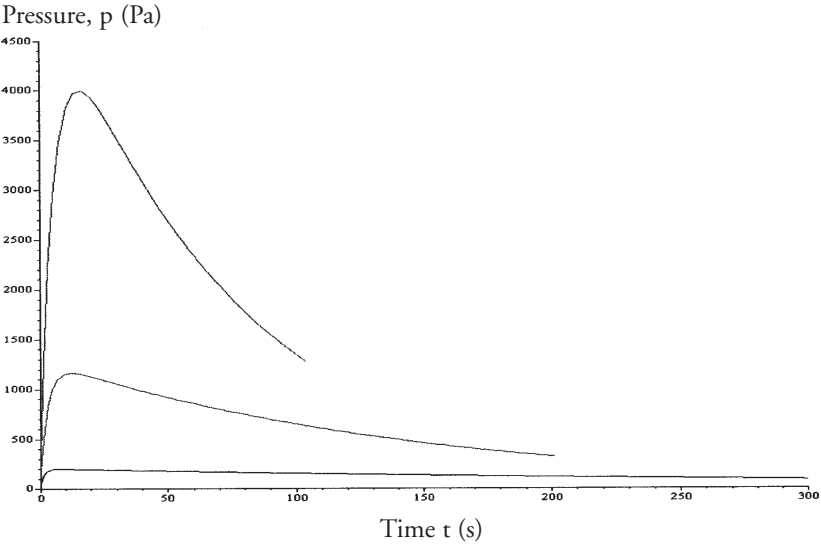
Pressure, p (Pa)

Figure 8.3   *Pressure change / time for different steady fires in the studied space with leakage area of 0.15 m^2 with heat release rate of 5 MW, 2,5 MW and 1 MW respectively counted downwards.*

Table 8.4   Pressure rise during fire with heat release rate of 5 MW as a function of temperature rise, Pa (according to the model).

Leakage area, m^2	Smoke layer temperature, K				
	400	600	800	1000	1200
0.15	4000	2700	1900	1500	1300
1.0	100	50	40	25	10

As it can be seen from the Table 8.3 and Table 8.4 there is one common characteristic trend in pressure behaviour during a steady fire, i.e. the pressure reduction. However, the pressure values differ - lower in the

66

dynamic model case then in the static case and the velocity of pressure reduction is less in the dynamic model case according to the equation 8.12 as in the comparison with the static model. These can depend on the more precise estimation of the fire progress in a space, where changing temperature velocity is counted.

Some more results concerning pressure/temperature changes in the designed space are presented in Figures 8.4 and 8.5.

Pressure p (Pa)
Temperature T (K)
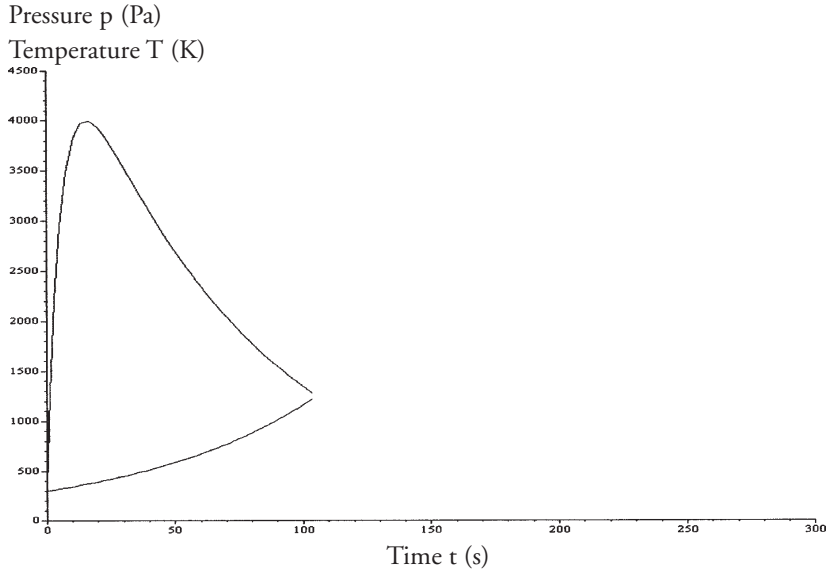
Figure 8.4   *Pressure and temperature change / time for a steady fire with heat release rate of 5 MW and leakage area of 0.15 m².*

Pressure p (Pa)
Temperature T (K)
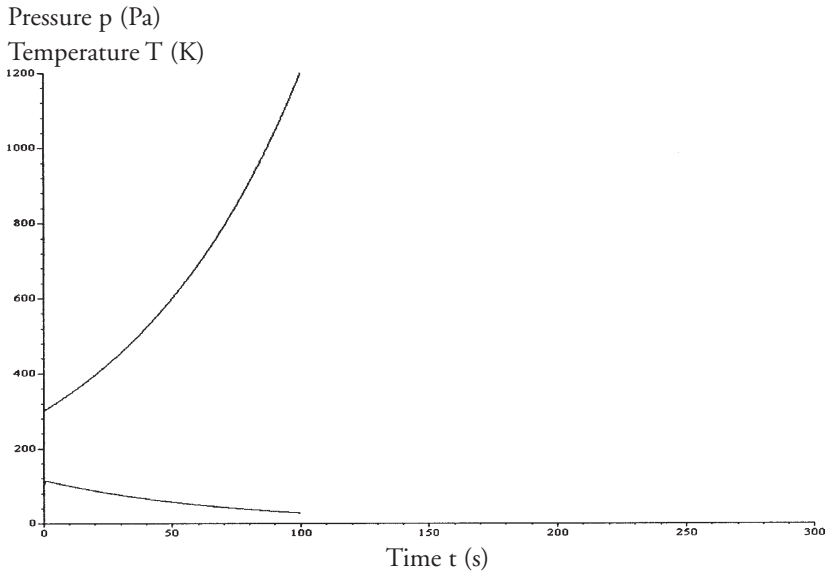
Figure 8.5   *Pressure and temperature change / time for a steady fire with heat release rate of 5 MW and leakage area of 1.0 m².*

One more simulation was made for the case with a "real" design industrial building in Sweden of 100x100x10m with standard even distributed leakage area of 3.5 m² and for a fire with heat release rate of 5 MW, 2,5 MW and 1 MW. Resulting pressure change is presented in the Figure 8.6.

As it is seen from the above-presented simulations for a "real" industrial building in Sweden of 100x100x10m with leakage area of 3.5 m² even distributed, the peak pressures expected here are essentially smaller then in the "little" space (Figure 8.3). Peak pressures reach 900 Pa, 230 Pa and 40 Pa for the fires with heat release rate of 5 MW, 2,5 MW and 1 MW respectively.

In order to compare pressure rise and mass change out of a room for the designed space a simulation for t^2-fires with the similar heat release rates was made. The results are presented in the Figure 8.7.
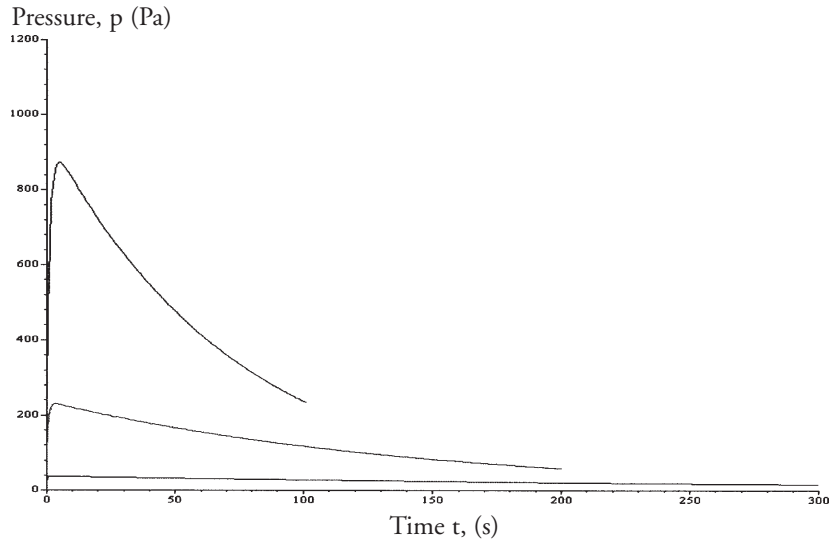
Pressure, p (Pa)

Figure 8.6   Pressure change / time for different steady fires in the space of 100000 m3 with leakage area of 3.5 m2 with heat release rate of 5 MW, 2,5 MW and 1 MW respectively counted downwards.

Total mass, m (kg)
Pressure rise, p (Pa)
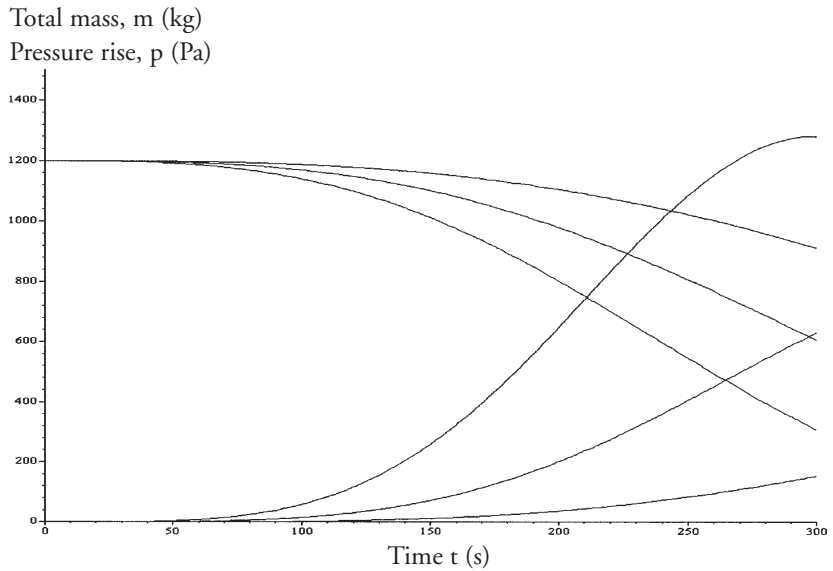
Figure 8.7   Pressure and mass change / time for different t²-fires with heat release rate of 5 MW, 2,5 MW and 1 MW respectively counted downwards for pressure rise and either inverted.

As it is seen from the Figure 8.7, it takes longer time for a t^2-fire to produce high pressure in the burning space in comparison with steady fires with the same heat release rate. The trend in pressure development is however the same: pressure increases during some time and then begins to decrease. Mass flow decreases during fire.

In order to evaluate pressure in the burning building wind pressure included, the following study was done.

Resulting pressure in a building effected by the wind with combination of opened smoke vents and windows/doors on the windward and/or leeward sides of the space along with fire pressure and/or buoyancy can be estimated with the help of the following method.

The problem is not linear and the computer program PFS was used as a tool. General description of the PFS is presented in subchapter 10.2.

9 Airtightness in industrial buildings

Airtightness as a concept and as typical values for small buildings was discussed in Gordonova (1998). The analysis furthermore describes this problem for the large spaces.

The expansion of gas caused by heat released during the fire increases the pressure in the compartment and drives some gas out of the room through leakage paths. All openings through which gas flows out are called vents. If a window is open in the room of fire origin little flow occurs through the remainder of the building. When doors and windows are closed and there are no ventilation openings, flow will move towards cracks and leaks wherever they may be in the room. All these flows are initially nonbuoyant. As the fire grows, hot gas flows buoyantly out of the place of origin, while cold gas flows in below. To evaluate gas flux (mass flow) out of the burning room and pressure circumstances in the room with the help of the simulation programs, it is essential to know the sizes of such vents.

Air leakage occurs as a consequence of building design, workmanship and materials used. The amount of air leakage depends on the magnitude of the driving forces in combination with the size and shape of the leakage paths. In the normal case, these driving forces are pressure differences across the structure, temperature differences between the inside and outside of the structure and, if there is one, the ventilation system.

For new non-residantial buildings, the standard requirements specified in Swedish Building Regulations, BBR 94, must be followed. According to BBR 94, air infiltration should not exceed 1.6 l/s,m^2 (6 m^3/h,m^2) for these types of buildings at 50 Pa pressure difference. This requirement relates to the area of the building envelope. The building envelope area is defined as the area exposed to outside air.

The objective of this evaluation is to summarise knowledge about the real magnitude of leakage for the industrial and large spaces, built at different times.

In different investigations, made both in Sweden and abroad, the problem of air leakage in different houses was analysed and air infiltration under different conditions was measured (Andrew K. Persily, 1999). This particular study presented air tightness data from a number of different studies as well in Sweden as abroad. The studies of the US industrial buildings relate to comparatively newly built houses of mean age of approximately 25 years. The age of buildings in the corresponding Swedish study was not available. In the Table 9.1 summary of air tightness data for the studied industrial buildings is presented.

Table 9.1   Summary of airtightness data.

| Dataset | Air leakage at 50 Pa, m^3/h, m^2 | | | |
	Mean	Standard deviation	Minimum	Maximum
Industrial, Sweden	4.65	2	2.2	8.3
Industrial, US	33.8	21.77	10.3	79.3

As it is seen from the table, Swedish construction traditions and airtightness requirements differ from those in the USA. All the presented air leakage in Swedish constructions converted into units of l/s,m^2 show good agreement with those required by the Swedish building codes.

A little bit older data for halls with steel building constructions is presented in Arne Elmroth's (1985). Mean air leakage in this study was 4.3 m^3/h, m^2 at the pressure difference of 50 Pa.

9.1   Assumed airtightness

For the purpose of this study the size of air leakage paths for Swedish buildings is determined by requirements in the Swedish Building Regulations, i.e. air leakage is assumed to be 6 m^3/h, m^2 relating to the area of the building's envelope. In order to have large-scaled outline, the case based on the above presented air leakage in the industrial buildings in the USA is studied. For this case air leakage of 60 m^3/h, m^2 relating to the area of the building envelope is chosen.

10 Calculation of resulting inner pressure in the space exposed to wind pressure

Resulting pressure in a space in case of a fire is effected by different pressures due to buoyancy, thermal expansion of indoor air and wind pressure on the building. The study presented in this chapter estimates this internal pressure as a function of resulting internal wind factor called here equivalent indoor wind factor. The resulting internal pressure determines flow direction through it. The study was made step-by-step:

– for the "cold" case without fire and ventilation,
– for the "cold" case without fire and with ventilation,
– for the fire case with somewhat ventilation unbalance.

10.1 Model: equivalent indoor wind factor

The flow direction for any leakage or opening is determined by the pressure difference between outside and inside. The wind creates both over and under pressure relative to the normal pressure far off the building. The internal pressure is not equal to this normal pressure but mostly somewhat less. This internal under pressure occurs for a building with even leakage distribution and due to the fact that most of the surfaces has negative wind factor and thereby under pressure. The only surfaces with the over pressure are those exposed to direct wind attack. This means for a cubic building that only one side will have over pressure if the wind is perpendicular to that side. The other four surfaces (roof included) all have under pressure.

Building internal pressure is a function of the external wind pressure on building surfaces. Combination of wind pressure on building and airtightness of the building along with opening of doors, windows in the walls and fire vents on the roof can result in great variations of pressure. Different openings can be opened at the windward and leeward sizes of building and roof at the same time. In order to evaluate indoor pressure under different circumstances the following model was done.

10.1.1 "Cold" case without fire and ventilation

Assume a building with a single space and n surfaces with wind factor m_j and leakage area of A_j, where index $j=1,n$. All outside external pressures relative to a point far off the building can be stated as

$$p_j = \mu_j\, p_c \tag{10.1}$$

where

p_c the characteristic wind pressure calculated as the dynamic pressure of the wind with the characteristic velocity v_c.

$$p_c = \rho\, v_c^2 / 2 \tag{10.2}$$

The inside internal pressure p_i is defined as

$$p_i = \mu_i\, p_c \tag{10.3}$$

with its equivalent wind factor μ_i which is unknown and has to be calculated.

If the equivalent internal wind factor μ_i is less than any wind factor outside close to an opening or a leakage path then there will be an inflow into the space, and if larger, then an outflow from the space.

Each leakage flow q_j independently of its direction can now be calculated assuming that the pressure drop for a leakage or an opening area is equal to the dynamic pressure for the flow velocity

$$v_j = q_j / A_j \tag{10.4}$$

A positive flow q_j is defined as an inflow into the building.

This gives the relation

$$\rho\, v_j^2 / 2 = \rho\, (\mu_j - \mu_i)\, v_c^2 / 2 \tag{10.5}$$

The flow q_j and the velocity v_j can be calculated regarding the sign as follows

$$q_j = A_j v_j = A_j \ f(\mu_j - \mu_i) v_c \qquad (10.6)$$

where the function $f(x) = f(\mu_j - \mu_i)$ with $x = \mu_j - \mu_i$
is defined as

$$f(x) = \begin{cases} \sqrt{x} & x > 0 \\ 0 & x = 0 \\ -\sqrt{-x} & x < 0 \end{cases} \qquad (10.7)$$

The total leakage balance flow $q(\mu_i)$ can be stated as the sum of all leakage flows which are a function of the internal wind factor μ_i

$$q(\mu_i) = \sum_{j=1}^{n} A_j \ f(\mu_j - \mu_i) v_c \qquad (10.8)$$

The densities are equal for inflows but can differ somewhat for outflows. For the sake of simplicity, the densities in the equation 10.8 are assumed to be equal.

For an unventilated building the total leakage flow $q(\mu_i)$ has to be zero (flow balance). This gives a possibility to solve the internal wind factor μ_i. The equation 10.8 can only be solved analytical for two surfaces (n=2), else numerical methods have to be used.

Assume a case with only two wind factors μ_a and μ_b and the corresponding areas A_a and A_b which could be sums of leakage areas with the same wind factor. Assume the leakage inflow and outflow is equal to q. The two pressure relations for the flow q in leakage or opening a and b becomes

$$(\mu_a - \mu_i) \frac{\rho v_c^2}{2} = \frac{\rho}{2} \left(\frac{q}{A_a} \right)^2 \qquad (10.9)$$

$$(\mu_i - \mu_b) \frac{\rho v_c^2}{2} = \frac{\rho}{2} \left(\frac{q}{A_b} \right)^2 \qquad (10.10)$$

The equivalent inside wind factor becomes then

$$\mu_i = \frac{(A_a^2 \ \mu_a + A_b^2 \ \mu_b)}{A_a^2 + A_b^2} \qquad (10.11)$$

Assuming that $\mu_b = 0$ and $\mu_a = 1$ this can be shown with the help of Figure 10.1.
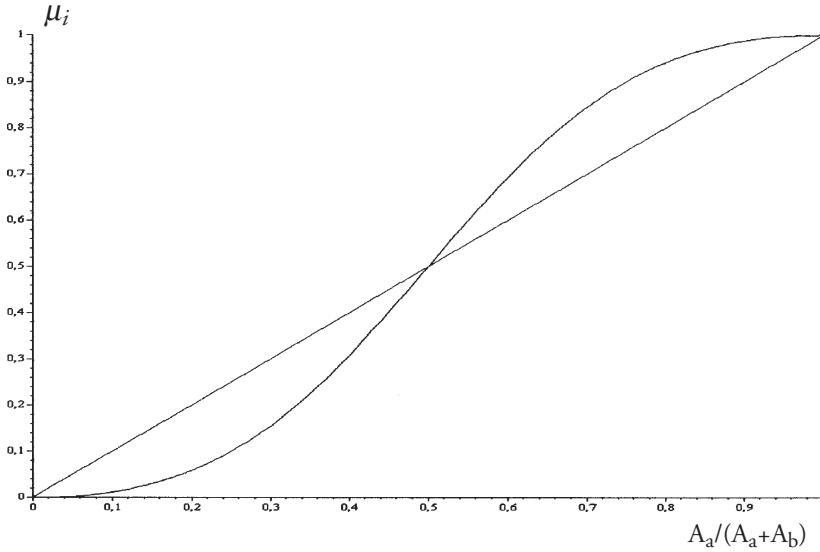
Figure 10.1   The equivalent internal wind factor as a function of envelope areas.

Example

Assume a cubic building with side area of 1 and with only one windward side with the wind factor of 0.8 and remaining four other sides with the wind factor of –0.4. The internal wind factor becomes then

$$\mu_i = (0.8 - 4^2 \times 0.4)/(1 + 4^2) = -0.33$$

10.1.2 The general case

The general case with more then two surfaces has to be solved numerically by a simple interval reduction scheme. The "μ_i" must be limited by the minimum and maximum wind factors, which gives

$$\mu_{\max} = \max (\mu_j) \tag{10.12}$$

$$\mu_{\min} = \min (\mu_j) \tag{10.13}$$

Compute the middle value of the search interval (μ_{min}, μ_{max}) as

$$\mu' = (\mu_{max} + \mu_{min})/2 \qquad (10.14)$$

Calculate the total flow balance $q(\mu')$ and update the search interval as follows. Flow in/out in the building, q

if $q(\mu') > 0$, then $\qquad \mu_{min} = \mu' \qquad (10.15)$

if $q(\mu') < 0$, then $\qquad \mu_{max} = \mu' \qquad (10.16)$

What pressure can one expect inside the building - negative or positive? If $\mu' = 0$, so

if $q(0) < 0$, then $\mu_i < 0$ $\qquad$ negative pressure, as expected

if $q(0) > 0$, then $\mu_i > 0$ $\qquad$ positive pressure, and

$$q_{ij}(0) = \Sigma v\, A_j\, \sqrt{\mu_j}$$

Example

Assume the layout of a building with a flow balance as it is presented below. Assuming that area of one side of the space is equal to A_a with μ_a, while each of three other sides has area A_b with μ_b
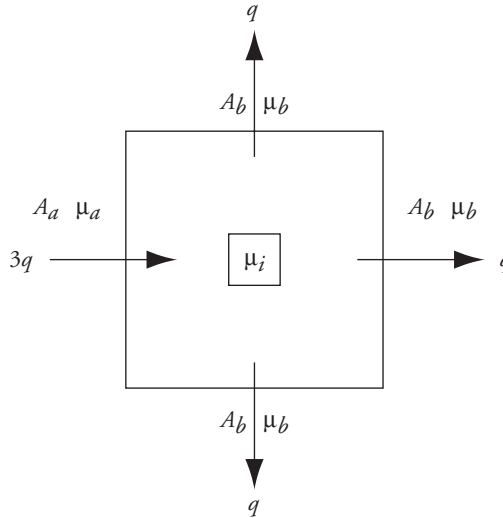
then

$$\frac{\rho}{2}\left(\frac{3q}{A_a}\right)^2 + \frac{\rho}{2}\left(\frac{q}{A_b}\right)^2 = (\mu_a - \mu_b)\frac{\rho}{2}v_c^2$$

$$10\,\frac{q^2}{A^2} = (\mu_a - \mu_b)v_c^2/2$$

$$(\mu_a - \mu_i)\frac{\rho\,v_c^2}{2} = \frac{\rho}{2}\left(\frac{3q}{A_a}\right)^2$$

$$(\mu_i - \mu_b)\frac{\rho\,v_c^2}{2} = \frac{\rho}{2}\left(\frac{q}{A_b}\right)^2$$

$$\mu_i = \mu_b + \frac{q^2}{A_b^2\,v_c^2}$$

$$\mu_i = \mu_b + (\mu_a - \mu_b)\frac{v_c^2}{10\,v_c^2}$$

$$\mu_i = \frac{(9\,\mu_b + \mu_a)}{10}$$

As it can be seen from the last equation for the majority of cases the internal pressure factor and, thus, internal pressure is less then zero. As soon as a $\mu_b < -1/9\mu_a$, it will be negative pressure in the place.

10.1.3 "Cold" case without fire and with ventilation

The wind flow balance will of course be influenced by an operating ventilation system. Many ventilation systems work deliberately with a somewhat larger exhaust flow than supply flow. This is done in order to create some under pressure to protect the building from condensation in the building's envelope. The wind flow balance can be extended to cover an operating ventilation system with an exhaust flow q_e and a supply flow q_s. Both flows are assumed to be constant and independent of the internal pressure p_i. The total flow balance now becomes

$$q(\mu_i) + q_s = q_e \tag{10.17}$$

This equation can be solved by simple interval reducing method as shown before.

10.1.4 Thermal case

The stock effect due to higher indoor temperature than outside especially if a smoke layer is sufficiently deep will of course improve the situation. The function of smoke ventilation can be estimated by calculating the wind induced pressure difference as

$$\Delta p_j = (\mu_j - \mu_i) p_c \qquad (10.18)$$

and comparing it with the stock effect

$$\Delta p_t = (\rho_0 - \rho_i) gh \qquad (10.19)$$

This is an approximation because all leaks are assumed to be at the floor level.

The more complicated cases with both wind affected parts of roof along with different pressures in the place when burning is analyzed with the help of the computer program PFS.

10.2 PFS-program

For the purpose of evaluating of smoke evacuation through roof vents and roof mounted fans, a computer program PFS was used. This program, developed and written by Lars Jensen, is based on the semi graphical circuit drawings and treats arbitrary flow systems of any structure and layout, any media, and any problem: design or investigation. The program manual for PFS includes three major reports and four reports with applications.

Some of the usually occurring PFS elements and symbols are as follows:

"+"	define flow direction downwards and to the right as positive
"-"	define flow direction upwards and to the left as negative
A_0,0.15:hq	describes en opening with area of 0.15 m^2, and prints out pressure change and flow in it
h?0	printout pressure
h?200	describes a fire with a flow of 200 l/s, downwards or t o the right, and prints out pressure
h?-200	describes flow of 200 l/s, upwards or to the left, and prints out pressure

h,100:q	describes pressure of 100 Pa and prints out flow
h,ps	describes pressure of ps Pa, computed before and prints out flow
h?:q	describes boundary case conditions and prints out pressure and flow in a room
q,0	describes boundary case's zero flow
s,value	describes some initial flow for calculation, which facilitates convergence
FF:hq<	describes a fan with flow direction upwards and to the left, and prints out pressure change and flow produced by this fan
FF:hq>	describes a fan with a flow direction downwards and to the right, and prints out pressure change and flow produced by this fan
t,10,50:q	describes an unit with quadratic pressure loss of 10 Pa at flow of 50 l/s and prints out flow
d,200,6	describes 6 m long ventilation duct of 200 mm diameter
UD	notation for outdoor air intake
TD	notation for transfer air device
:t	resulting inner pressure in the studied space.

10.3 Models to estimate resulting pressure in the space exposed to wind pressure with different openings in the walls and on the roof

Typical values for a wind blowing perpendicular to one side of an isolated, low, square building with a flat roof (Figure 10.2) is recommended by the SFPA Handbook of Fire Protection Engineering to be +0.7 to windward, -0.5 on the sides.
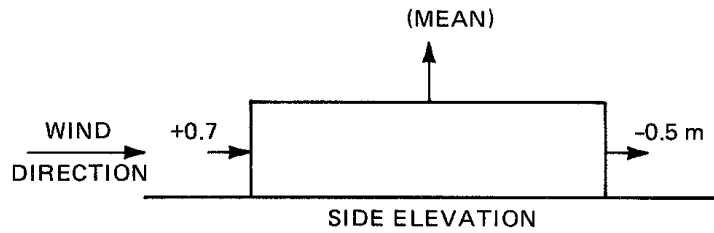
Figure 10.2   Square coefficients for an isolated, low, square building [The SFPA Handbook of Fire Protection Engineering].

The corresponding "schematic"-layout of a space with one windward wall, three leeward walls and windward half of the roof and leeward half of the roof is presented in Figure 10.3.
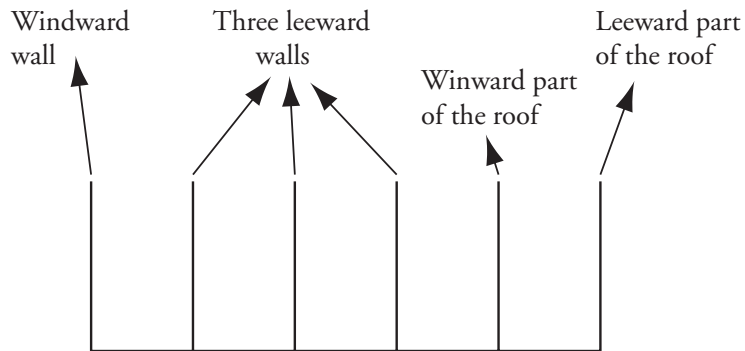
Figure 10.3   The " schematic " layout of the space

For the case of this study, the positive values for roofs are of interest. For pitched roofs one side (windward) would be 0.2, while the other one -0.2.

The corresponding PFS-layout of a building presented above with the ordinary leakage paths of 1.5 cm^2/m^2 exposed to different wind pressures at the wind speed of 5 m/s is presented in Figure 10.4.

```
begin  my1w.1a1
parameter r=1.25 v=5
parameter m1=0.7 m2=-0.4 m3=-0.4 m4=-0.4 m5=0.2 m6=-0.2
compute pv=r*v*v/2
compute p1=m1*pv
compute p2=m2*pv
compute p3=m3*pv
compute p4=m4*pv
compute p5=m5*pv
compute p6=m6*pv
set Ao=t,0.6

•h,p1         •h,p2        •h,p3        •h,p4        •h,p5        •h,p6
•Ao,0.15:qh  •Ao,0.15:qh  •Ao,0.15:qh  •Ao,0.15:qh  •Ao,0.15:qh  •Ao,0.15:qh
|            |            |            |            |            |
|            |            |            |            |            |
|            |            |            |            |            |
+————————————+————————————+———————•————+————————————+————————————+
                                   :t
end
```

Figure 10.4   PFS-layout of the schematic model. (Se page 77).

10.3.1 Studied cases to evaluate the resulting pressure in the space

Six cases were studied:

–   with closed doors, inlet openings and smoke vents,
–   with opened smoke vent of 1 m^2 on the leeward roof side
–   with opened smoke vent of 1 m^2 on the windward roof side
–   with opened smoke vents of 1 m^2 each on the both leeward and windward roof sides
–   with opened smoke vents of 1 m^2 each on the both leeward and windward roof sides plus an opened door of 1 m^2 on the windward wall
–   with opened smoke vents of 1 m^2 each on the both leeward and windward roof sides plus an opened door of 1 m^2 on the leeward wall

All the studied cases are presented in Table 10.1

Table 10.1 List of the studied cases

Cases	Doors	Inlet openings	Smoke vents
1	Closed	Closed	Closed
2	Closed	Closed	1 m^2 on the leeward side
3	Closed	Closed	1 m^2 on the windward side
4	Closed	Closed	1 m^2 each on the windward and leeward sides
5	1 m^2 on the windward wall	Closed	1 m^2 each on the windward and leeward sides
5	1 m^2 on the leeward wall	Closed	1 m^2 each on the windward and leeward sides

```
begin  my1w.1a1
parameter r=1.25 v=5
parameter m1=0.7 m2=-0.4 m3=-0.4 m4=-0.4 m5=0.2 m6=-0.2
compute pv=r*v*v/2
compute p1=m1*pv
compute p2=m2*pv
compute p3=m3*pv
compute p4=m4*pv
compute p5=m5*pv
compute p6=m6*pv
set Ao=t,0.6

Case 1
All openings are closed (airtightness is 15 cm²/m²)

 •h,p1        •h,p2        •h,p3        •h,p4        •h,p5        •h,p6
 •Ao,0.15:qh •Ao,0.15:qh •Ao,0.15:qh •Ao,0.15:qh •Ao,0.15:qh •Ao,0.15:qh
 │           │           │           │           │           │
 │           │           │           │           │           │
 │           │           │           │           │           │
 +-----------+-----------+-----------+-----------+-----------+-----------+
                         :t

Case 2
All openings are closed besides on the leeward roof side (airtightness is
15 cm²/m²)

 •h,p1        •h,p2        •h,p3        •h,p4        •h,p5        •h,p6
 •Ao,0.15:qh •Ao,0.15:qh •Ao,0.15:qh •Ao,0.15:qh •Ao,0.15:qh •Ao,1:qh
 │           │           │           │           │           │
 │           │           │           │           │           │
 │           │           │           │           │           │
 +-----------+-----------+-----------+-----------+-----------+-----------+
                         :t

Case 3
All openings are closed besides windward roof side (airtightness is 15
cm²/m²)

 •h,p1        •h,p2        •h,p3        •h,p4        •h,p5        •h,p6
 •Ao,0.15:qh •Ao,0.15:qh •Ao,0.15:qh •Ao,0.15:qh •Ao,1:qh     •Ao,0.15:qh
 │           │           │           │           │           │
 │           │           │           │           │           │
 │           │           │           │           │           │
 +-----------+-----------+-----------+-----------+-----------+-----------+
                         :t

Case 4
All openings are closed besides two openings on the both windward and
leeward roof sides (airtightness is 15 cm²/m²)

 •h,p1        •h,p2        •h,p3        •h,p4        •h,p5        •h,p6
 •Ao,0.15:qh •Ao,0.15:qh •Ao,0.15:qh •Ao,0.15:qh •Ao,1:qh     •Ao,1:qh
 │           │           │           │           │           │
 │           │           │           │           │           │
 │           │           │           │           │           │
 +-----------+-----------+-----------+-----------+-----------+-----------+
                         :t

Case 5
All openings are closed besides one opening in the windward wall and two
openings on the both windward and leeward roof sides (airtightness is 15
cm²/m²)

 •h,p1        •h,p2        •h,p3        •h,p4        •h,p5        •h,p6
 •Ao,1:qh     •Ao,0.15:qh •Ao,0.15:qh •Ao,0.15:qh •Ao,1:qh     •Ao,1:qh
 │           │           │           │           │           │
 │           │           │           │           │           │
 │           │           │           │           │           │
 +-----------+-----------+-----------+-----------+-----------+-----------+
                         :t

Case 6
All openings are closed besides one opening in the leeward wall and two
openings on the both windward and leeward roof sides (airtightness is 15
cm²/m²)

 •h,p1        •h,p2        •h,p3        •h,p4        •h,p5        •h,p6
 •Ao,0.15:qh •Ao,1:qh     •Ao,0.15:qh •Ao,0.15:qh •Ao,1:qh     •Ao,1:qh
 │           │           │           │           │           │
 │           │           │           │           │           │
 │           │           │           │           │           │
 +-----------+-----------+-----------+-----------+-----------+-----------+
                         :t

end
```

Figure 10.5   PFS-layout of the schematic model.

```
begin   c:\bind\my1.1a1
parameter r=1.25 v=5
parameter m1=0.7 m2=-0.4 m3=-0.4 m4=-0.4 m5=0.2 m6=-0.2
compute pv=r*v*v/2                                     =      15.625000
compute p1=m1*pv                                       =      10.937500
compute p2=m2*pv                                       =      -6.250000
compute p3=m3*pv                                       =      -6.250000
compute p4=m4*pv                                       =      -6.250000
compute p5=m5*pv                                       =       3.125000
compute p6=m6*pv                                       =      -3.125000
set Ao=t,0.6

Case 1
All openings are closed (airtightness is 15 cm2/m2)

 •h,p1         •h,p2         •h,p3         •h,p4         •h,p5         •h,p6
 •Ao,0.15:qh •Ao,0.15:qh •Ao,0.15:qh •Ao,0.15:qh •Ao,0.15:qh •Ao,0.15:qh
 | -13.7 Pa  |    3.4 Pa  |    3.4 Pa  |    3.4 Pa  |   -5.9 Pa  |    0.3 Pa  |
 | 0.718 m3/s|-0.360 m3/s|-0.360 m3/s|-0.360 m3/s| 0.471 m3/s|-0.110 m3/s|
 |           |           |           |           |           |           |
 +-----------+-----------+-----------+-----------+-----------+-----------+
                              •:t
                             -2.8 Pa

Case 2
All openings are closed besides leeward roof side (airtightness is 15
cm2/m2)

 •h,p1         •h,p2         •h,p3         •h,p4         •h,p5         •h,p6
 •Ao,0.15:qh •Ao,0.15:qh •Ao,0.15:qh •Ao,0.15:qh •Ao,0.15:qh •Ao,1:qh
 | -14.0 Pa  |    3.1 Pa  |    3.1 Pa  |    3.1 Pa  |   -6.2 Pa  |    0.0 Pa  |
 | 0.726 m3/s|-0.343 m3/s|-0.343 m3/s|-0.343 m3/s| 0.483 m3/s|-0.179 m3/s|
 |           |           |           |           |           |           |
 +-----------+-----------+-----------+-----------+-----------+-----------+
                              •:t
                             -3.1 Pa

Case 3
All openings are closed besides leeward roof side (airtightness is 15
cm2/m2)

 •h,p1         •h,p2         •h,p3         •h,p4         •h,p5         •h,p6
 •Ao,0.15:qh •Ao,0.15:qh •Ao,0.15:qh •Ao,0.15:qh •Ao,1:qh    •Ao,0.15:qh
 |  -9.1 Pa  |    8.0 Pa  |    8.0 Pa  |    8.0 Pa  |   -1.3 Pa  |    4.9 Pa  |
 | 0.586 m3/s|-0.549 m3/s|-0.549 m3/s|-0.549 m3/s| 1.491 m3/s|-0.429 m3/s|
 |           |           |           |           |           |           |
 +-----------+-----------+-----------+-----------+-----------+-----------+
                              •:t
                              1.8 Pa

Case 4
All openings are closed besides two openings on the both windward and
leeward roof sides (airtightness is 15 cm2/m2)

 •h,p1         •h,p2         •h,p3         •h,p4         •h,p5         •h,p6
 •Ao,0.15:qh •Ao,0.15:qh •Ao,0.15:qh •Ao,1:qh    •Ao,1:qh    •Ao,1:qh
 | -11.9 Pa  |    5.3 Pa  |    5.3 Pa  |    5.3 Pa  |   -4.0 Pa  |    2.2 Pa  |
 | 0.667 m3/s|-0.447 m3/s|-0.447 m3/s|-0.447 m3/s| 2.595 m3/s|-1.919 m3/s|
 |           |           |           |           |           |           |
 +-----------+-----------+-----------+-----------+-----------+-----------+
                              •:t
                             -0.9 Pa

Case 5
All openings are closed besides one opening in the windward wall and two
openings on the both windward and leeward roof sides (airtightness is 15
cm2/m2)

 •h,p1         •h,p2         •h,p3         •h,p4         •h,p5         •h,p6
 •Ao,1:qh    •Ao,0.15:qh •Ao,0.15:qh •Ao,0.15:qh •Ao,1:qh    •Ao,1:qh
 |  -8.4 Pa  |    8.7 Pa  |    8.7 Pa  |    8.7 Pa  |   -0.6 Pa  |    5.6 Pa  |
 | 3.752 m3/s|-0.573 m3/s|-0.573 m3/s|-0.573 m3/s| 1.026 m3/s|-3.060 m3/s|
 |           |           |           |           |           |           |
 +-----------+-----------+-----------+-----------+-----------+-----------+
                              •:t
                              2.5 Pa

Case 6
All openings are closed besides one opening in the leeward wall and two
openings on the both windward and leeward roof sides (airtightness is 15
cm2/m2)

 •h,p1         •h,p2         •h,p3         •h,p4         •h,p5         •h,p6
 •Ao,0.15:qh •Ao,1:qh    •Ao,0.15:qh •Ao,0.15:qh •Ao,1:qh    •Ao,1:qh
 | -13.7 Pa  |    3.5 Pa  |    3.5 Pa  |    3.5 Pa  |   -5.9 Pa  |    0.3 Pa  |
 | 0.718 m3/s|-2.399 m3/s|-0.360 m3/s|-0.360 m3/s| 3.141 m3/s|-0.740 m3/s|
 |           |           |           |           |           |           |
 +-----------+-----------+-----------+-----------+-----------+-----------+
                              •:t
                             -2.8 Pa

end 1  6 problems  78 elements  0 errors  0 warnings  2000-09-14  16.12.02
```

Figure 10.6   PFS-result of the schematic model.

Parameter ":t" shows resulting inner pressure in the studied space. Its value varies from under pressure of –3.1 Pa to over pressure of 2.5 Pa depending on place and area of opening.

As this study shows, a single opening can change the internal pressure completely. Wind factor is mostly negative which also means that the equivalent internal wind factor is negative and can be less then wind factor over the roof. This means that smoke ventilation will not function as designed.

11 Design parameters

For the purpose of this study design parameters should be estimated. These parameters include space examined, weather data, fire and smoke layer characteristics, and values for ventilation systems.

11.1 Design space, leakage paths, roof type and ventilation systems

Size	100×100×10 m^3.
Air leakage area	3.5 m^2.
Roof type	Gable, pentroof, hipped, butterfly, arched (windward side μ=0.2, leeward side μ=-0.2).
Ventilation systems	Smoke vents, exhaust, supply, smoke fan (combination).

11.2 Design weather data

There are little weather data for the design of smoke control and smoke management systems. For the purpose of this study some extreme outdoor temperatures and extreme wind velocities are chosen as the valid parameters. Such low (winter case)/high (summer case) outdoor temperatures as well as extreme wind velocities occur for short periods of time. However, they can cause problems with smoke management, as there is no time lag for smoke dealing systems. Problems from stack effect wintertime and reverse stack effect summertime may result. For that reason, outdoor temperatures of -20°C, 0°C and 20°C are chosen in this

study. Extreme wind velocity of 25 m/s is chosen as the max reference wind velocity. The above presented assumption coincide with the 1999 ASHRAE Handbook, Heating, Ventilation and Air-Conditioning Applications, Chapter 51, where extreme outdoor winter and summer temperatures and extreme wind data are recommended as design parameters for smoke management. Such data presented in 1997 ASHRAE Handbook, Fundamentals is very close, if not the same, to the values assumed here.

Along with these extreme parameters, more usual temperature of 0°C and wind velocities of 5 and 10 m/s were also tested.

11.3   Design fire

Ideally the design fire should show the physical size and heat output of the fire increasing with time, allowing the threat to occupants to be calculated as time increases. The variety of variations of fire growth curves makes it practically impossible to choose a reasonable fire size and fire growth velocity. Hence, the steady fire of some maximum size a fire can be expected to reach during the escape period seems to be a reasonable assumption here. A vast variations in heat release rates of fires in large spaces leads to certain assumptions of the designed fire size. The fire size chosen here is similar to recommended by Klote and Mike: 5 MW, 1992.

Fire type	Steady fire
Released Heat Rate	5 MW

11.4   Design smoke layer

Temperature	400°C
Depth of layer (under the roof)	6 m

11.5 Design Ventilation Fans

An average characteristic air change rate of 2 1/h with corresponding airflow of 60 m^3/s is chosen for the study. Hence, design ventilation fans have the following capacity:

Supply fan	60 m^3/s at 444 Pa
Exhaust fan	60 m^3/s at 444 Pa

Both the exhaust and supply ventilation systems have duct network. The above-presented parameters were chosen according to average fan capacity for ventilation systems of this size.

Additional mechanical exhaust ventilation should provide airflow approximately the same rate as smoke produced. For the heat released rate of 5 MW the maximum expected fire flow never exceeds 15 m^3/s. This airflow is a maximum theoretically possible airflow due to expansion under assumption that all heat released warms the air volume in space. As a matter of fact, heat loss due to convection, radiation, etc can vary a lot. The most realistic value of such losses can vary from 70% to 50%. Hence, the expected fire flow due to expansion can vary from 5 m^3/s through 10 m^3/s to 15 m^3/s. For the study en average value of 10 m^3/s is chosen. Design smoke fan has following capacity:

Smoke fan	10 m^3/s at 60 Pa.

The above-presented parameters were chosen according to average fan capacity for ventilation systems of this size.

12   Models and tools

The study presented in these chapter estimates the resulting internal pressure in terms of flow direction in/out via smoke vents.

An analysis of the schematic models, evaluation of the wrong/right function of smoke vents in the studied space with/without fire and with running/non-running ordinary ventilation systems is presented in this chapter.

12.1   Real and schematic models of the space

The main principals of describing the fire space with openings on the leeward and windward parts of the walls and the roof along with the running ventilation system(s), and its analyses are presented in this chapter. The real and schematic layouts of the analysed space are shown in Figures 12.1 and 12.2.
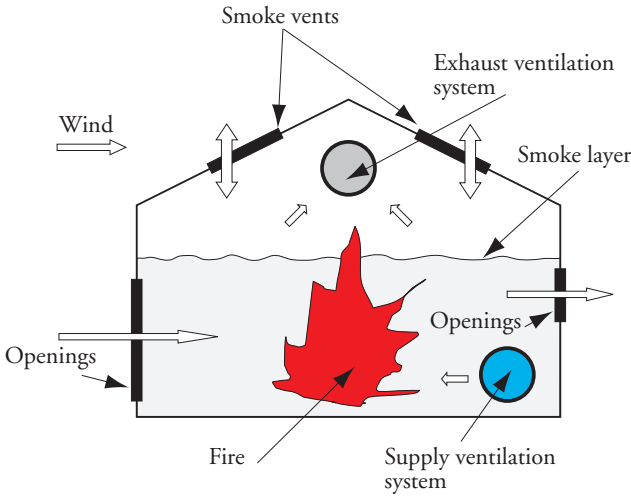
Figure 12.1   The "real" layout of the space.
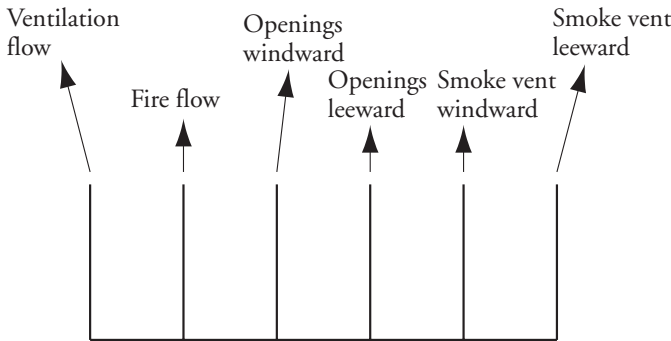
Figure 12.2   The " schematic " layout of the space.

The study comprises:

- general study of principal cases, i.e. evaluation of smoke vents function in unventilated buildings with no thermal forces (cold case),
- study of principal cases for the ordinary conditions without fire (without buoyancy) at the indoor temperature of 20°C, i.e. evaluation of smoke vents function in unventilated buildings with indoor temperature of 400 °C (fire case),

- evaluation of smoke vents function in buildings ventilated by either supply or exhaust system with indoor temperature of 400 °C (fire case),
- evaluation of smoke evacuation with the help of roof mounted smoke fans with or without roof vents in buildings ventilated by supply-exhaust system and with indoor temperature of 400 °C (fire case).

12.2   General study of principal cases

The purpose of this study is to evaluate resulting equivalent internal pressure in the space versus outdoor pressure and as a result of it the amount of roof vents with reversed flow (inlet flow instead of outlet).

Nine different cases have been studied. These cases comprise different combination of opened versus closed openings on the windward and/or leeward sides of walls, roof smoke vents of different areas exposed to different outdoor temperatures and wind velocities. Ventilation system's influence has also been evaluated here in a simplified way as a ventilation balance versus unbalance in the examined space.

Table 12.1   List on the studied cases with different combination of opened/
                 closed openings in the walls and smoke vents on the roof in the
                 studied space.

N case	Opened area, m^2			
	Walls		Smoke vents	
	Windward	Leeward	Windward	Leeward
1	-	-	-	-
2	2	-	-	2
3	6	-	-	2
4	12	-	-	2
5	-	-	2	2
6	2	-	2	2
7	2	2	2	2
8	-	2	2	2
9	2	-	2	-

Above presented cases were studied at

- different climatic conditions
    with outdoor air temperatures of –20°C,
    0 °C and 20°C and
    wind velocity of 5 m/s, 10 m/s and 25
    m/s; along with
- different indoor air temperatures of 20 °C and 400°C (fire case).

Besides that the model was studied with

- positive ventilation balance flow (running supply ventilation system only),
- zero ventilation balance (not running ventilation systems) and
- negative ventilation balance flow (running exhaust ventilation system only).

12.3   Study of principal cases for the ordinary conditions without fire

The purpose of this study is to evaluate outflow/inflow via smoke vents under above described conditions. Smoke vents are located on the both leeward and windward sides of the roof. It means that indicated case with inlet flow through the roof vents could occur through one or both of them. This is reflected in the resulted percentile amount of "fault" smoke vents.

Results for the studied cases for a space at the ordinary indoor temperature of 20°C are shown in Table 12.2.

Table 12.2   Number of roof vents with inlet flow in percent versus amount of cases with inlet flow via the roof vents in percent for the design case with variations in airflow (cold case).

Wind velocity, m/s	Ventilation flow, m^3/s	$T_o = 20°C$	$T_o = 0°C$	$T_o = -20°C$
5	0	40/70	25/50	15/30
25	0	40/70	40/70	40/70
5	5	22.5/40	15/30	5/0
25	5	37.5/70	30/70	35/70
5	-5	47.5/70	35/70	20/40
25	-5	40/70	40/70	40/70

As it is seen from the Table 12.2 temperature difference between inside and outside air influences the amount of reversed (inlet) flow through the roof vents only at the wind velocity of 5 m/s. Obviously, the determining factor in reversed function of the roof vents is wind velocity. In the "summer" case with the same amount of inlet roof vents for both wind velocities, the numerical values of inlet flows were considerably higher for 25 m/s.

At the same time, difference between values of inlet flows via the roof vents at different outdoor temperatures are negligible for wind velocity of 25 m/s. As it can be seen, positive ventilation balance (supply ventilation system in operation) reduces the amount of inlet flows in the roof vents in comparison with a case with no ventilation at all.

The results of this study is of interest for the case when buoyancy is insufficient, for example at low fire smoke temperatures or after the fire smoke been chilled by sprinklers.

12.4 Study of principal cases for the fire conditions (with buoyancy) at the indoor temperature of 400°C

The purpose of this study is to evaluate outflow/inflow via smoke vents in the case of fire with a 400°C smoke filled space.

Results of studied cases are shown in Table 12.3.

Table 12.3   Number of roof vents with inlet flow in percent versus amount of cases with inlet flow via the roof vents in percent for the case with a smoke filled building, T_s=400°C.

Wind velocity, m/s	No ventilation	Supply ventilation in operation, stopped exhaust ventilation system, airflow of 5 m^3/s	Exhaust ventilation system in operation, stopped supply ventilation system, airflow of -5 m^3/s
5	0/0	0/0	0/0
25	25/50	25/50	25/50

As it is seen from the Table 12.3, both the exhaust and the supply ventilation systems separately in operation, along with high indoor temperature have no effect on the amount of roof vents with reversed flow. Nevertheless, even in this special case increasing wind velocity results in increased "error" roof vent's behavior. Numerically, these undesirable inlet flows through the roof vents are somewhat higher in the case with the exhaust ventilation system in operation than with the supply ventilation system in operation, that is on its part higher then without ventilation system at all. The pattern is characteristic to all cases.

Comparison between the Table 12.2 and Table 12.3 shows that buoyancy has undoubtedly valuable effect on the resulting pressure conditions and therefore on the amount of inlets through the smoke vents.

12.5   Study of cases for the fire conditions with constant ventilation flows

The purpose of this study is to examine the above studied space filled with 400°C smoke more detailed when ventilated with constant ordinary ventilation flow. The above-presented study was completed with additional cases No 6, 11, 12, 13. All in all, thirteen cases were studied. Case 6 corresponds to the smoke vents area of 200 m^2 even distributed (2% of the floor area of the space). This case corresponds to the requirements in the Swedish Building Codes, BBR.

Table 12.4   List on the studied cases with different combination of opened/ closed openings in the walls and smoke vents on the roof in the studied space.

N case	Opened area, m^2			
	Walls		Smoke vents	
	Windward	Leeward	Windward	Leeward
1	-	-	-	-
2	3	-	-	2
3	6	-	-	2
4	12	-	-	2
5	-	-	2	2
6	-	-	100	100
7	2	-	2	2
8	2	2	2	2
9	-	2	2	2
10	2	-	2	-
11	-	2	-	2
12	12	-	-	-
13	-	11	-	-

Cases were studied with either constant supply ventilation flows or similar constant exhaust ventilation flows of about 2 l/h – 60 m^3/s and 3 l/h – 80 m^3/s.

However, it is important to notice, that these cases do not cover the entire range of possible variations in areas of openings, nor do they comprise all thinkable variations in their combinations.

Table 12.5   Number of roof vents with inlet flow in percent contra amount of cases with inlet flow via the roof vents in percent for the design case with a smoke filled building and either supply or exhaust ventilation system in operation with permanently constant air flow.

Wind velocity, m/s	Ventila-tion systems stopped	Ventilation system in operation			
		Supply ventilation system in operation		Exhaust ventilation system in operation	
		Flow: $60 \text{ m}^3/\text{s}$ (2 l/h)	Flow: $80 \text{ m}^3/\text{s}$ (3 l/h)	Flow: $-60 \text{ m}^3/\text{s}$ (2 l/h)	Flow: $-80 \text{ m}^3/\text{s}$ (3 l/h)
5	4/8	4/8	4/8	42/62	62/69
25	27/54	15/31	8/15	46/77	50/77

As it is seen from the Table 12.5 exhaust and supply ventilation systems each along with high indoor temperature have clear effect on the amount of reversed flow through the roof vents. Nevertheless, even in this special case increasing wind velocity results in increased "error" smoke vent's behavior. Numerically this undesirable inlet flows through the roof vents are somewhat higher in the case with the supply ventilation system in operation, but the pattern is characteristic to the both "positive" and "negative" ventilation flows.

The above studied cases with smoke filled space are extreme cases. They were important for evaluating of upper limit for result values. Such cases are interesting neither for fire fighting operations, nor for safe egress. The case with a height of smoke layer that is 2/3 of the height of the building is more appropriate and correct for the smoke management. The studies similar to the above-presented analyses were made for this reduced height of the smoke layer (6 m). The results differ from the above-presented value inessential and therefore are not showed here.

Six meters smoke layer height under the roof (four meters of clear air above the floor), along with wind velocity of 25 m/s are assumed to be design parameters for the further analyses.

13 " Real case" study

The study presented in previous Chapter 12 refers to a somewhat simplified ventilation system with positive (supply) and negative (exhaust) ventilation with constant flows. In this chapter, the problem of smoke movements through smoke roof vents will be evaluated regarding the ventilation systems installed.

13.1 Evaluation of smoke vents function in buildings ventilated by either supply or exhaust system with different type of regulation

In spite of the fact that a great variety of different ventilation systems is used in the large spaces, three major types depending on the type of regulation were studied:

- without any control,
- with a constant air flow (air volume control) and
- with a constant pressure drop in the ventilation system (pressure control).

Ventilation fan curve is described by a simplified equation

$$\Delta p = a\,n^2 + b\,n\,q + c\,q^2 \tag{13.1}$$

where

Δp pressure, Pa
a, b, c coefficients, -
q air flow, m^3/s
n revolution, -/min

Calculations were made for the fan with the following characteristics.

| Pressure, Pa | 500 | 444 | 100 |
| Air flow, l/s | 0 | 60 | 160 |

The model tested here illustrates the designed space of 10^5 m^3 with fire expansion flow of 10 m^3/s and with the ordinary ventilation flow, both supply and exhaust, equal to 60 m^3/s (approximately two 1/h). The smoke layer is six meters high under the roof (four meters of clear air above the floor) with the temperature of 400°C. Designed wind velocity is 25 m/s. The schematic and corresponding PFS - layouts of the analysed space are shown in Figures 13.1 and 13.2.
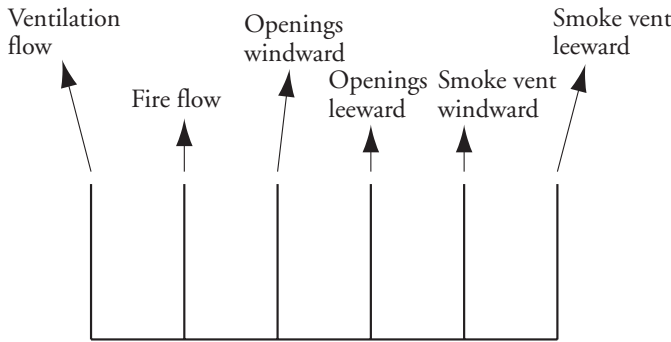
Figure 13.1   The " schematic " layout of the space.

In the fire case increasing pressure in the space results in decreasing supply airflow in the supply duct-network and increasing airflow in the exhaust duct-network. If both ventilation systems have air flow control, then in the supply ventilation system it appears that pressure in the system will increase in order to restore diminishing duct flow, while the exhaust ventilation system on the opposite will throttle air flow in order to compensate for increasing fire flow. Pressure control can be of two major different types: with pressure detectors in the system's plenum – outdoor and with pressure detectors in the fire room – in the system's plenum. Ventilation systems with pressure control of the first type were examined here. Pressure drop control of the second type results as a matter of fact in constant airflow. Results are presented in the Table 13.1 and in the Figure 13.3.

```
smoke   smokw117
begin
format     - - - - 1
control    rsaee=1e-5
parameter  v=25.0     qtf=10  Ti=400    To=20    g=9.81    r=1.25
parameter  f1=0.8    f2=-0.4   f3=0.2    f4=-0.2
parameter  pd=444   qd=60   n=1.7 nm=0.4
compute    s6=1.2*(273+Ti)*(1/(273+Ti)-1/(273+To))*g*6
compute    p1=f1*r*v*v/2
compute    p2=f2*r*v*v/2
compute    p3=f3*r*v*v/2
compute    p4=f4*r*v*v/2
set        1m2=t,0.6,1:h  3m2=t,0.6,3:h  0.5m2=t,0.6,0.5:h
set        6m2=t,0.6,6:h 12m2=t,0.6,12:h 100m2=t,0.6,100:h
set        0m=h,0        6m=h,s6          tryck=h?qtf:q
fan        FF 500:0 pd:qd 100:160
set        agg=g,pd,qd,n
```

Case 1 "leakage"
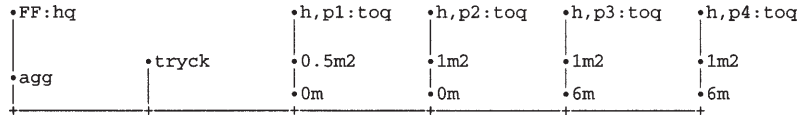
Case 2 "windward 1w+1r"

Case 3 "windward 2w+1r"
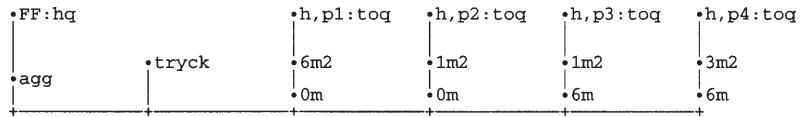
Case 4 "windward 4w+1r"
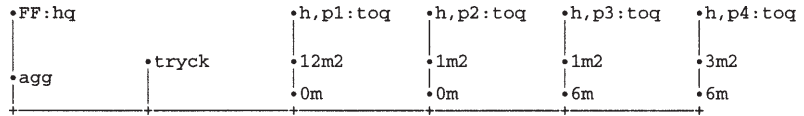
Case 5 "roof"
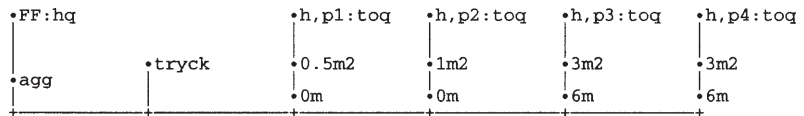
Case 6 "roof200m2"

Figure 13.2   PFS-layout of the tested model (beginning).

```
Case 7 "roof+windward"
 •FF:hq                        •h,p1:toq   •h,p2:toq   •h,p3:toq   •h,p4:toq
 |                             |           |           |           |
 |                •tryck       •3m2        •1m2        •3m2        •3m2
 •agg             |            |           |           |           |
 |                |            •0m         •0m         •6m         •6m
 +----------------+------------+-----------+-----------+-----------+
Case 8 "open"
 •FF:hq                        •h,p1:toq   •h,p2:toq   •h,p3:toq   •h,p4:toq
 |                             |           |           |           |
 |                •tryck       •3m2        •3m2        •3m2        •3m2
 •agg             |            |           |           |           |
 |                |            •0m         •0m         •6m         •6m
 +----------------+------------+-----------+-----------+-----------+
Case 9 "roof+leeward"
 •FF:hq                        •h,p1:toq   •h,p2:toq   •h,p3:toq   •h,p4:toq
 |                             |           |           |           |
 |                •tryck       •0.5m2      •3m2        •3m2        •3m2
 •agg             |            |           |           |           |
 |                |            •0m         •0m         •6m         •6m
 +----------------+------------+-----------+-----------+-----------+
Case 10 "wwrf+www"
 •FF:hq                        •h,p1:toq   •h,p2:toq   •h,p3:toq   •h,p4:toq
 |                             |           |           |           |
 |                •tryck       •3m2        •1m2        •3m2        •1m2
 •agg             |            |           |           |           |
 |                |            •0m         •0m         •6m         •6m
 +----------------+------------+-----------+-----------+-----------+
Case 11 "lwrf+lww"
 •FF:hq                        •h,p1:toq   •h,p2:toq   •h,p3:toq   •h,p4:toq
 |                             |           |           |           |
 |                •tryck       •0.5m2      •3m2        •1m2        •3m2
 •agg             |            |           |           |           |
 |                |            •0m         •0m         •6m         •6m
 +----------------+------------+-----------+-----------+-----------+
Case 12 "windward 4w+leakage"
 •FF:hq                        •h,p1:toq   •h,p2:toq   •h,p3:toq   •h,p4:toq
 |                             |           |           |           |
 |                •tryck       •12m2       •1m2        •1m2        •1m2
 •agg             |            |           |           |           |
 |                |            •0m         •0m         •6m         •6m
 +----------------+------------+-----------+-----------+-----------+
Case 13 "windward 4l+leakage"
 •FF:hq                        •h,p1:toq   •h,p2:toq   •h,p3:toq   •h,p4:toq
 |                             |           |           |           |
 |                •tryck       •0.5m2      •12m2       •1m2        •1m2
 •agg             |            |           |           |           |
 |                |            •0m         •0m         •6m         •6m
 +----------------+------------+-----------+-----------+-----------+
end
```

Figure 13.2   PFS-layout of the tested model (end).

```
smoke   c:\bind\smoke117
begin
format      - - - - 1
control     rsaee=1e-5
parameter   v=25.0     qtf=10  Ti=400    To=20    g=9.81    r=1.25
parameter   f1=0.8     f2=-0.4  f3=0.2    f4=-0.2
parameter   pd=444   qd=60   n=1.7 nm=0.4
compute     s6=1.2*(273+Ti)*(1/(273+Ti)-1/(273+To))*g*6  =      -91.604645
compute     p1=f1*r*v*v/2                                 =      312.500000
compute     p2=f2*r*v*v/2                                 =     -156.250000
compute     p3=f3*r*v*v/2                                 =       78.125000
compute     p4=f4*r*v*v/2                                 =      -78.125000
set         1m2=t,0.6,1:h  3m2=t,0.6,3:h  0.5m2=t,0.6,0.5:h
set         6m2=t,0.6,6:h 12m2=t,0.6,12:h 100m2=t,0.6,100:h
set         0m=h,0          6m=h,s6            tryck=h?qtf:q
fan         FF 500:0 pd:qd 100:160
set         agg=g,pd,qd,n
```

Case 1 "leakage"

```
•FF:hq      486.1 Pa       •h,p1:toq   •h,p2:toq   •h,p3:toq   •h,p4:toq
│ 465.6 Pa                 │ 312.5 Pa  │-156.2 Pa  │  78.1 Pa  │ -78.1 Pa
│  47.1 m3/s               │   7.7 m3/s│ -23.4 m3/s│ -17.6 m3/s│ -23.8 m3/s
│          •tryck          •0.5m2      •1m2        •1m2        •1m2
•agg       │ 171.4 Pa      │-141.1 Pa  │ 327.6 Pa  │ 184.9 Pa  │ 341.1 Pa
│          │  10.0 m3/s    •0m         •0m         •6m         •6m
+----------+---------------+-----------+-----------+-----------+
```

Case 2 "windward 1w+1r"

```
•FF:hq                     •h,p1:toq   •h,p2:toq   •h,p3:toq   •h,p4:toq
│ 462.9 Pa                 │ 312.5 Pa  │-156.2 Pa  │  78.1 Pa  │ -78.1 Pa
│  48.9 m3/s               │  49.4 m3/s│ -22.6 m3/s│ -16.5 m3/s│ -69.2 m3/s
│          •tryck          •3m2        •1m2        •1m2        •3m2
•agg       │ 149.7 Pa      │-162.8 Pa  │ 305.9 Pa  │ 163.2 Pa  │ 319.4 Pa
│          │  10.0 m3/s    •0m         •0m         •6m         •6m
+----------+---------------+-----------+-----------+-----------+
```

Case 3 "windward 2w+1r"

```
•FF:hq                     •h,p1:toq   •h,p2:toq   •h,p3:toq   •h,p4:toq
│ 472.5 Pa                 │ 312.5 Pa  │-156.2 Pa  │  78.1 Pa  │ -78.1 Pa
│  42.1 m3/s               │  70.7 m3/s│ -25.3 m3/s│ -20.1 m3/s│ -77.4 m3/s
│          •tryck          •6m2        •1m2        •1m2        •3m2
•agg       │ 229.2 Pa      │ -83.3 Pa  │ 385.5 Pa  │ 242.7 Pa  │ 399.0 Pa
│          │  10.0 m3/s    •0m         •0m         •6m         •6m
+----------+---------------+-----------+-----------+-----------+
```

Case 4 "windward 4w+1r"

```
•FF:hq                     •h,p1:toq   •h,p2:toq   •h,p3:toq   •h,p4:toq
│ 478.7 Pa                 │ 312.5 Pa  │-156.2 Pa  │  78.1 Pa  │ -78.1 Pa
│  37.1 m3/s               │  84.6 m3/s│ -27.0 m3/s│ -22.2 m3/s│ -82.4 m3/s
│          •tryck          •12m2       •1m2        •1m2        •3m2
•agg       │ 282.7 Pa      │ -29.8 Pa  │ 439.0 Pa  │ 296.2 Pa  │ 452.5 Pa
│          │  10.0 m3/s    •0m         •0m         •6m         •6m
+----------+---------------+-----------+-----------+-----------+
```
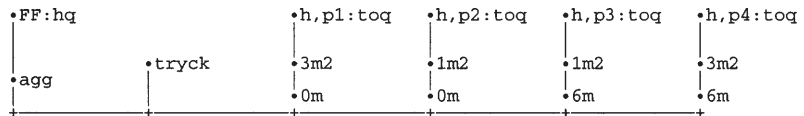
Case 5 "roof"

```
•FF:hq                     •h,p1:toq   •h,p2:toq   •h,p3:toq   •h,p4:toq
│ 444.1 Pa                 │ 312.5 Pa  │-156.2 Pa  │  78.1 Pa  │ -78.1 Pa
│  59.9 m3/s               │  11.4 m3/s│ -16.2 m3/s│ -14.6 m3/s│ -50.6 m3/s
│          •tryck          •0.5m2      •1m2        •3m2        •3m2
•agg       │   0.7 Pa      │-311.8 Pa  │ 157.0 Pa  │  14.2 Pa  │ 170.5 Pa
│          │  10.0 m3/s    •0m         •0m         •6m         •6m
+----------+---------------+-----------+-----------+-----------+
```

Case 6 "roof200m2"

```
•FF:hq                     •h,p1:toq   •h,p2:toq   •h,p3:toq   •h,p4:toq
│ 432.7 Pa                 │ 312.5 Pa  │-156.2 Pa  │  78.1 Pa  │ -78.1 Pa
│  65.8 m3/s               │  12.9 m3/s│ -10.8 m3/s│1101.5 m3/s│ -1179 m3/s
│          •tryck          •0.5m2      •1m2        •100m2      •100m2
•agg       │ -86.3 Pa      │-398.8 Pa  │  70.0 Pa  │ -72.8 Pa  │  83.5 Pa
│          │  10.0 m3/s    •0m         •0m         •6m         •6m
+----------+---------------+-----------+-----------+-----------+
```

Figure 13.3   PFS-results of the tested model (beginning).

```
Case 7 "roof+windward"

  •FF:hq                      •h,p1:toq   •h,p2:toq    •h,p3:toq    •h,p4:toq
  | 455.3 Pa                  | 312.5 Pa  |-156.2 Pa   | 78.1 Pa   | -78.1 Pa
  |  53.6 m3/s                |  58.0 m3/s| -20.2 m3/s| -39.1 m3/s| -62.2 m3/s
  |            •tryck         •3m2        •1m2         •3m2         •3m2
  •agg         | 88.6 Pa      |-223.9 Pa  | 244.8 Pa  | 102.1 Pa  | 258.3 Pa
  |            | 10.0 m3/s    •0m         •0m          •6m          •6m
  +------------+--------------+-----------+-----------+-----------+

Case 8 "open"

  •FF:hq                      •h,p1:toq   •h,p2:toq    •h,p3:toq    •h,p4:toq
  | 447.8 Pa                  | 312.5 Pa  |-156.2 Pa   | 78.1 Pa   | -78.1 Pa
  |  57.9 m3/s                |  65.1 m3/s| -52.8 m3/s| -25.5 m3/s| -54.7 m3/s
  |            •tryck         •3m2        •3m2         •3m2         •3m2
  •agg         | 29.8 Pa      |-282.7 Pa  | 186.1 Pa  |  43.3 Pa  | 199.6 Pa
  |            | 10.0 m3/s    •0m         •0m          •6m          •6m
  +------------+--------------+-----------+-----------+-----------+

Case 9 "roof+leeward"

  •FF:hq                      •h,p1:toq   •h,p2:toq    •h,p3:toq    •h,p4:toq
  | 441.4 Pa                  | 312.5 Pa  |-156.2 Pa   | 78.1 Pa   | -78.1 Pa
  |  61.3 m3/s                |  11.8 m3/s| -45.3 m3/s|  9.6 m3/s| -47.5 m3/s
  |            •tryck         •0.5m2      •3m2         •3m2         •3m2
  •agg         | -19.6 Pa     |-332.1 Pa  | 136.6 Pa  |  -6.2 Pa  | 150.1 Pa
  |            | 10.0 m3/s    •0m         •0m          •6m          •6m
  +------------+--------------+-----------+-----------+-----------+

Case 10 "wwrf+www"

  •FF:hq                      •h,p1:toq   •h,p2:toq    •h,p3:toq    •h,p4:toq
  | 466.4 Pa                  | 312.5 Pa  |-156.2 Pa   | 78.1 Pa   | -78.1 Pa
  |  46.5 m3/s                |  44.8 m3/s| -23.6 m3/s| -53.7 m3/s| -24.1 m3/s
  |            •tryck         •3m2        •1m2         •3m2         •1m2
  •agg         | 178.4 Pa     |-134.1 Pa  | 334.7 Pa  | 191.9 Pa  | 348.2 Pa
  |            | 10.0 m3/s    •0m         •0m          •6m          •6m
  +------------+--------------+-----------+-----------+-----------+

Case 11 "lwrf+lww"

  •FF:hq                      •h,p1:toq   •h,p2:toq    •h,p3:toq    •h,p4:toq
  | 440.1 Pa                  | 312.5 Pa  |-156.2 Pa   | 78.1 Pa   | -78.1 Pa
  |  62.1 m3/s                |  11.9 m3/s| -43.5 m3/s|  5.3 m3/s| -45.8 m3/s
  |            •tryck         •0.5m2      •3m2         •1m2         •3m2
  •agg         | -30.1 Pa     |-342.6 Pa  | 126.2 Pa  | -16.6 Pa  | 139.6 Pa
  |            | 10.0 m3/s    •0m         •0m          •6m          •6m
  +------------+--------------+-----------+-----------+-----------+

Case 12 "windward 4w+leakage"

  •FF:hq                      •h,p1:toq   •h,p2:toq    •h,p3:toq    •h,p4:toq
  | 481.5 Pa                  | 312.5 Pa  |-156.2 Pa   | 78.1 Pa   | -78.1 Pa
  |  34.6 m3/s                |  34.6 m3/s| -27.8 m3/s| -23.1 m3/s| -28.2 m3/s
  |            •tryck         •12m2       •1m2         •1m2         •1m2
  •agg         | 307.5 Pa     |  -5.0 Pa  | 463.8 Pa  | 321.0 Pa  | 477.3 Pa
  |            | 10.0 m3/s    •0m         •0m          •6m          •6m
  +------------+--------------+-----------+-----------+-----------+

Case 13 "windward 4l+leakage"

  •FF:hq                      •h,p1:toq   •h,p2:toq    •h,p3:toq    •h,p4:toq
  | 428.4 Pa                  | 312.5 Pa  |-156.2 Pa   | 78.1 Pa   | -78.1 Pa
  |  67.8 m3/s                |  13.4 m3/s| -95.2 m3/s| 13.2 m3/s| -9.2 m3/s
  |            •tryck         •0.5m2      •12m2        •1m2         •1m2
  •agg         |-118.5 Pa     |-431.0 Pa  | 37.8 Pa   |-105.0 Pa  | 51.3 Pa
  |            | 10.0 m3/s    •0m         •0m          •6m          •6m
  +------------+--------------+-----------+-----------+-----------+

end 1  14 problems  197 elements  0 errors  1 warning  2001-01-25  11.49.51
```
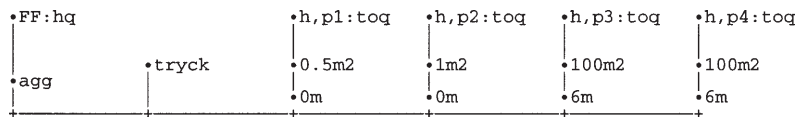
Figure 13.3   PFS-results of the tested model (end).

Table 13.1   Amount of roof vents with inlet flow in percent contra amount of cases with inlet flow via the roof vents in percent for the design case and different types of regulation of either supply or exhaust ventilation system in operation.

Ventilation system	Type of control			
	Constant air flow, 60 m^3/s	Constant air flow, 80 m^3/s	Constant pressure drop	No control
Supply ventilation system in operation	15/31	8/15	27/46	15/31
Exhaust ventilation system in operation	46/77	50/77	35/69	42/77

As it is seen from the Table 13.1, each of the exhaust and supply ventilation systems in operation, along with high indoor temperature has clear effect on the roof vents behavior. This effect depends on the type of ventilation system and it's regulation type. In the case with supply ventilation system increased airflow results in diminished amount of undesirable inlet flows through the roof vents, while the constant pressure drop makes the situation worth. In the case with running exhaust ventilation system, on the opposite, increased airflow do not improve the situation (numerically these undesirable inlet flows through the roof vents are somewhat lower), while the constant pressure drop improves the situation. Results correspond to the main principles described in Lars Jensen, 1993.

13.2   Evaluation of smoke vents function in buildings ventilated by supply-exhaust ventilation system along with or without roof mounted smoke fan

Here, the problem of smoke evacuation is evaluated regarding the supply-exhaust ventilation system and roof mounted smoke fan installed.

The following study examined effect of the usual supply-exhaust ventilation system along with variations in opening of smoke vents and/or roof mounted smoke fans. The model tested here illustrates the design space with the ordinary ventilation flow, both supply and exhaust, equal to 60 m^3/s (approximately two /h).

Moreover, the study comprises the above-presented cases of the smoke vents opening (Table 12.4) with additional variations in ventilation systems function.

Calculations were made for the supply and exhaust fans with the same characteristics as in Subchapter 13.1 and for the fire smoke fan with the following characteristics.

Pressure, Pa	100	60	10
Air flow, l/s	0	10	20

The schematic and PFS - layouts of the analysed space are shown in Figures 13.4 and 13.5. Results are presented in Table 13.2.
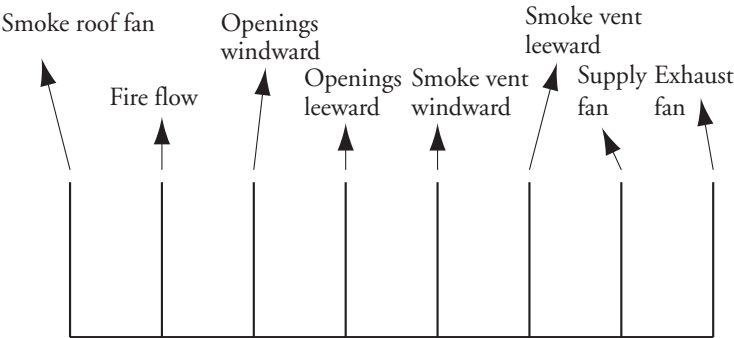
Figure 13.4   The " schematic " layout of the space.

```
smoke    smokw130
begin
format      - - - - 1
control     rsaee=1e-5
parameter   v=25.0      qtf=10   Ti=400    To=20    g=9.81    r=1.25
parameter   f1=0.8    f2=-0.4   f3=0.2    f4=-0.2
parameter   pd=444   qd=60   n=1.7 nm=0.4
compute     s6=1.2*(273+Ti)*(1/(273+Ti)-1/(273+To))*g*6
compute     p1=f1*r*v*v/2
compute     p2=f2*r*v*v/2
compute     p3=f3*r*v*v/2
compute     p4=f4*r*v*v/2
set         1m2=t,0.6,1:h  3m2=t,0.6,3:h  0.5m2=t,0.6,0.5:h
set         6m2=t,0.6,6:h 12m2=t,0.6,12:h 100m2=t,0.6,100:h
set         0m=h,0        6m=h,s6           tryck=h?qtf:q
fan         FS 100:0 60:10 10:20
fan         FF 500:0 pd:qd 100:160
set         agg=g,pd,qd,n
```

Case 1 "leakage"
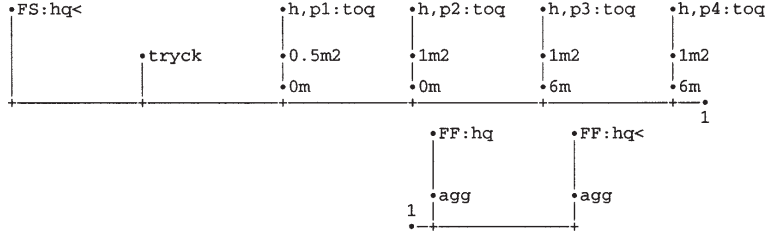
Case 2 "windward 1"
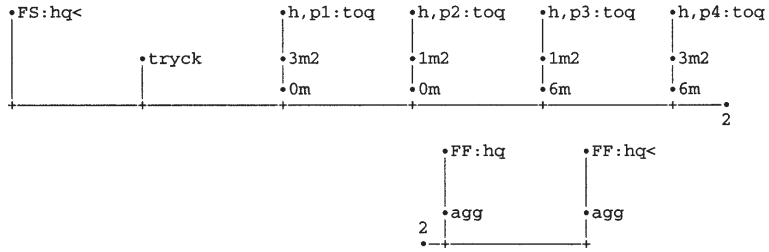
Case 3 "windward 2w+1r"

Case 4 "windward 4w+1r"

Figure 13.5   PFS-layout of the tested model (beginning).

```
Case 5 "roof"
 •FS:hq<                        •h,p1:toq    •h,p2:toq    •h,p3:toq    •h,p4:toq
        |                            |            |            |            |
        |          •tryck       •0.5m2       •1m2         •3m2         •3m2
        |              |             |            |            |            |
        |              |        •0m          •0m          •6m          •6m
        +--------------+-------------+------------+------------+------------•
                                                                            5
                                              •FF:hq        •FF:hq<
                                                   |             |
                                              •agg          •agg
                                          5   |    |             |
                                              •—+-----------------+

Case 6 "roof200m2"
 •FS:hq<                        •h,p1:toq    •h,p2:toq    •h,p3:toq    •h,p4:toq
        |                            |            |            |            |
        |          •tryck       •0.5m2       •1m2         •100m2       •100m2
        |              |             |            |            |            |
        |              |        •0m          •0m          •6m          •6m
        +--------------+-------------+------------+------------+------------•
                                                                            6
                                              •FF:hq        •FF:hq<
                                                   |             |
                                              •agg          •agg
                                          6   |    |             |
                                              •—+-----------------+

Case 7 "roof+windward"
 •FS:hq<                        •h,p1:toq    •h,p2:toq    •h,p3:toq    •h,p4:toq
        |                            |            |            |            |
        |          •tryck       •3m2         •1m2         •3m2         •3m2
        |              |             |            |            |            |
        |              |        •0m          •0m          •6m          •6m
        +--------------+-------------+------------+------------+------------•
                                                                            7
                                              •FF:hq        •FF:hq<
                                                   |             |
                                              •agg          •agg
                                          7   |    |             |
                                              •—+-----------------+

Case 8 "open"
 •FS:hq<                        •h,p1:toq    •h,p2:toq    •h,p3:toq    •h,p4:toq
        |                            |            |            |            |
        |          •tryck       •3m2         •3m2         •3m2         •3m2
        |              |             |            |            |            |
        |              |        •0m          •0m          •6m          •6m
        +--------------+-------------+------------+------------+------------•
                                                                            1
                                              •FF:hq        •FF:hq<
                                                   |             |
                                              •agg          •agg
                                          1   |    |             |
                                              •—+-----------------+

Case 9 "roof+leeward"
 •FS:hq<                        •h,p1:toq    •h,p2:toq    •h,p3:toq    •h,p4:toq
        |                            |            |            |            |
        |          •tryck       •0.5m2       •3m2         •3m2         •3m2
        |              |             |            |            |            |
        |              |        •0m          •0m          •6m          •6m
        +--------------+-------------+------------+------------+------------•
                                                                            2
                                              •FF:hq        •FF:hq<
                                                   |             |
                                              •agg          •agg
                                          2   |    |             |
                                              •—+-----------------+
```
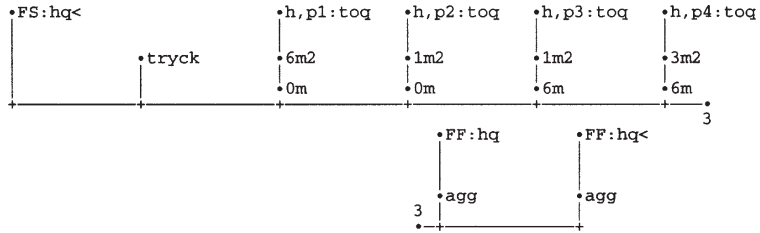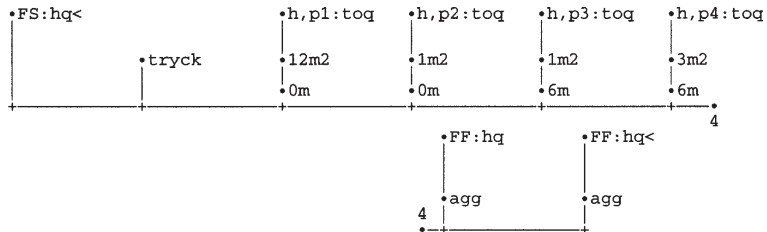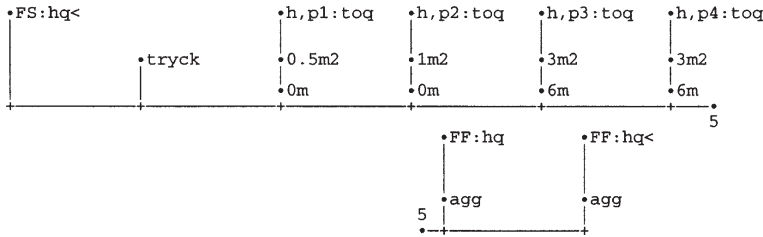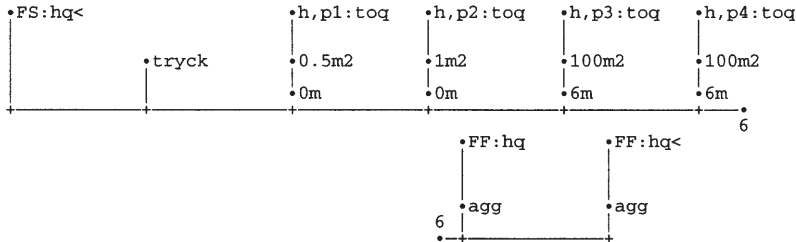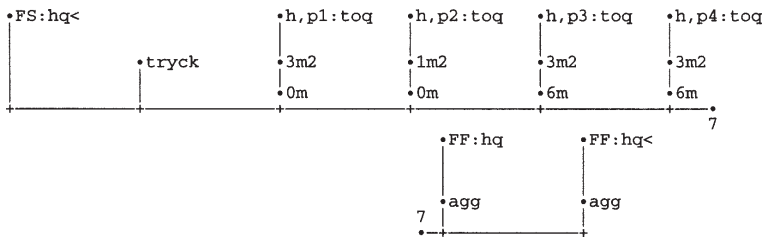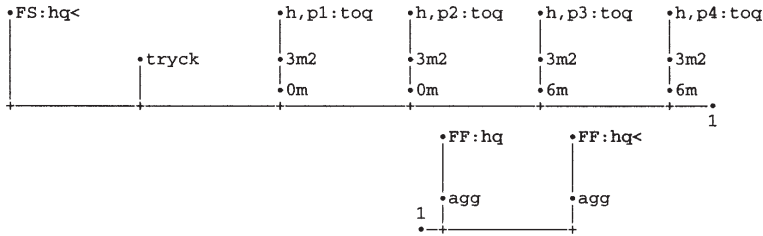
Figure 13.5   PFS-layout of the tested model (continuing).

108

```
Case 10 "wwrf+www"
 •FS:hq<                         •h,p1:toq   •h,p2:toq   •h,p3:toq   •h,p4:toq

              •tryck            •3m2        •1m2        •3m2        •1m2
                               •0m         •0m         •6m         •6m
 +-----------------+------------+-----------+-----------+-----------+-----•
                                                                          3

                                           •FF:hq       •FF:hq<

                                           •agg         •agg
                                        3 |
                                          •-+-----------+

Case 11 "lwrf+lww"
 •FS:hq<                         •h,p1:toq   •h,p2:toq   •h,p3:toq   •h,p4:toq

              •tryck            •0.5m2      •3m2        •1m2        •3m2
                               •0m         •0m         •6m         •6m
 +-----------------+------------+-----------+-----------+-----------+-----•
                                                                          4

                                           •FF:hq       •FF:hq<

                                           •agg         •agg
                                        4 |
                                          •-+-----------+

Case 12 "windward 4w+leakage"
 •FS:hq<                         •h,p1:toq   •h,p2:toq   •h,p3:toq   •h,p4:toq

              •tryck            •12m2       •1m2        •1m2        •1m2
                               •0m         •0m         •6m         •6m
 +-----------------+------------+-----------+-----------+-----------+-----•
                                                                          5

                                           •FF:hq       •FF:hq<

                                           •agg         •agg
                                        5 |
                                          •-+-----------+

Case 13 "windward 4l+leakage"
 •FS:hq<                         •h,p1:toq   •h,p2:toq   •h,p3:toq   •h,p4:toq

              •tryck            •0.5m2      •12m2       •1m2        •1m2
                               •0m         •0m         •6m         •6m
 +-----------------+------------+-----------+-----------+-----------+-----•
                                                                          6

                                           •FF:hq       •FF:hq<

                                           •agg         •agg
                                        6 |
                                          •-+-----------+

end
```
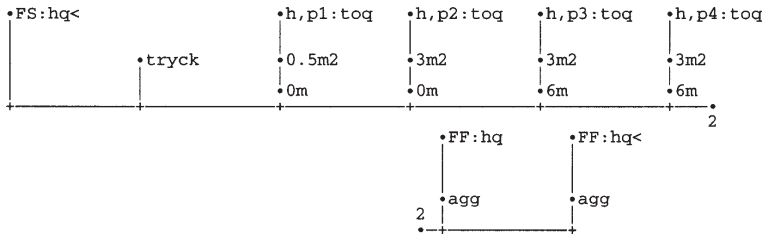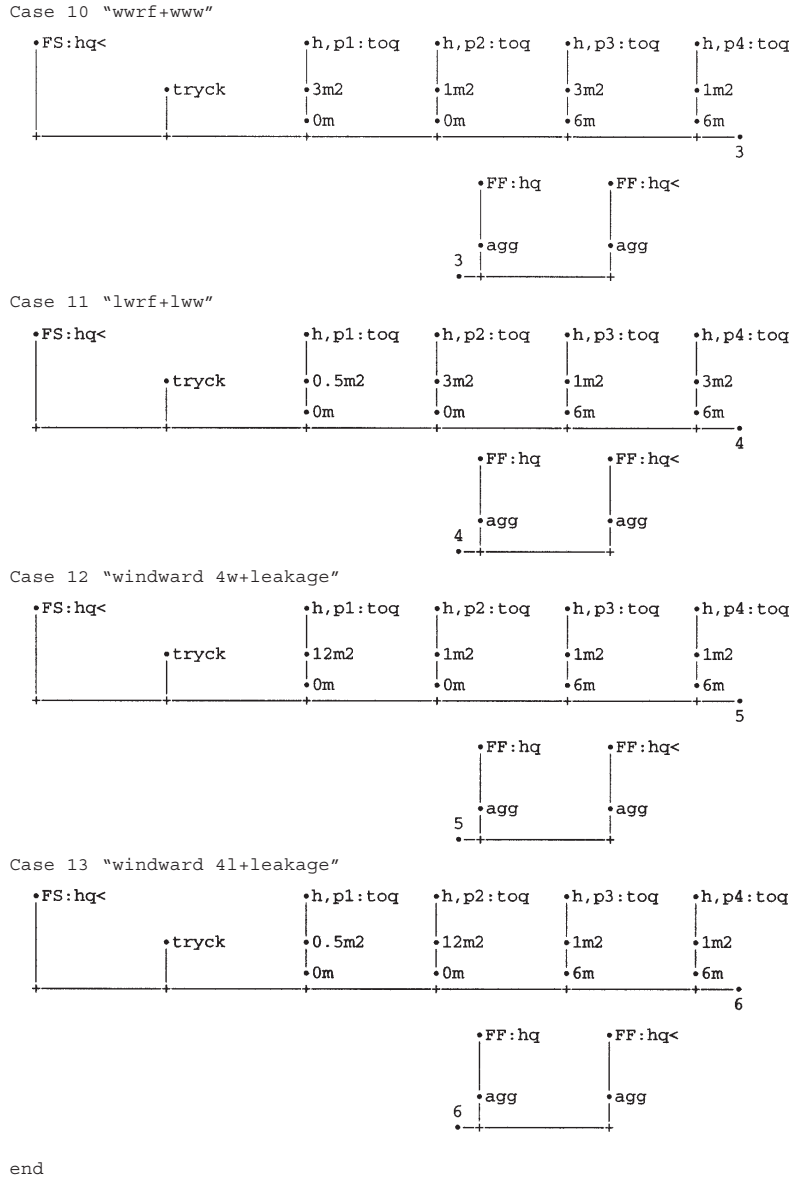
Figure 13.5   PFS-layout of the tested model (end).

Table 13.2   Data regarding the examined cases and the resulting number of
             smoke vents/cases with inlet flow in percent for smoke egress in
             the studied space.

Case	Supply fan	Exhaust fan	Fire smoke fan	Number of smoke vents/cases with inlet flow, %
1	Normal	Normal	-	27/54
2	Closed	Closed	-	19/38
3	Closed	Normal	-	39/77
4	Normal	Closed	-	15/31
5	Forced to 200 m^3/s (6 l/h)	Closed	-	8/15
6	Normal	Normal	Normal	35/70
7	Normal	Normal	Normal (without roof vents)	22/43 **(7fall)**
8	Closed	Closed	Normal (without roof vents)	22/43 **(7fall)**
9	Normal	Closed	Normal (without roof vents)	7/14 **(7 fall)**
10	Normal	Closed	Normal	15/30
11	Closed	Normal	Normal (without roof vents)	36/72 **(7 fall)**
12	Closed	Normal	Normal	35/70
13	Closed	Closed	Normal	23/46

As seen in Table 13.2 the minimum amount of inlets via the smoke roof vents in case 9 almost coincides with those in case 5.

The best results regarding smoke evacuation efficiency occur on the whole with working supply ventilation system regardless of type of smoke evacuating measures (cases 4, 5, 9, 10). Hence, the combination of working supply fan along with different combination of smoke evacuating measures can be considered as an effective measure. Supply ventilation outlets are supposed to be placed near the floor.

Difference between the smoke evacuating devices such as the ordinary smoke vents, smoke fan(s) and both of them along with not running ventilation systems is marginal. The efficiency of the chosen measure should be evaluated for the particular space under the particular conditions.

Using running supply and exhaust ventilation systems along with different combination of smoke evacuating devices showed slightly worse results then corresponding cases with shut down fans. The worst measure is combination of the shut down supply fan, working exhaust fan along with smoke evacuating devices.

Above presented analysis was made in terms of smoke vents reversed/ "wrong" function. It does not comprise more detailed analysis of flow's distribution between different air terminal devices, nor does it estimate fan's capacity to manage new "fire flow" conditions. In some of studied cases pressure condition in the simulated space was beyond fan's performance curve.

14   Cooling effect of sprinklers

The interaction between sprinklers and the operation of smoke vents has been studied and discussed in numerous research and studies. The mail goal of all studies was to evaluate how sprinklers operation is affected by smoke vents operation. This is commonly analyzed in terms of positive contra negative claims of combined usage of sprinklers and smoke vents.

The most common positive claim in this connection is that smoke vents prevent an excessive number of sprinklers from operating by limiting the spread of heat and smoke.

The most common negative claims in this connection are as follows:

- smoke vents can delay sprinkler activation and as a result can cause large fires by diminishing gas temperatures at ceiling level,
- smoke vents can increase the number of activated sprinklers as the result of above presented cause,
- smoke vent flow rates can be insufficient due to diminished buoyancy and thus are not cost effective.

There are studies that prove the above-presented issues along with studies that question them.

The focus of such studies is sprinklers, not smoke vents.

Here the attempt was made to evaluate this issue inversely, i.e. with the focus on smoke vents affected by sprinklers. The most important expected result of sprinkled fire contra unsprinklered fire from this point of view is cooling effect of sprinklers on ambient air and smoke layer. The resulting parameters are lower temperature equally distributed in the studied space, lower buoyancy and pressure due to expansion. Hence, effectiveness of smoke vents might diminish as a result of lower internal pressure.

The study of evaporative cooling by corridor sprinkler system made by Liu Stanley T., 1977 shows that

- spray with a smaller weight mean droplet diameter is more effective in cooling down the hot combustion products,
- it is possible for the spray to create a recirculating flow so that the combustion products will flow back into the burning room,
- a smaller sprinkler that produces a smaller mean droplet size under the same water flow rate is more effective than a larger sprinkler in the cooling of the combustion products.

This can be illustrated with the following algorithm. For the same volume of water V from sprinklers with droplets of different diameter, d, yields

$$V = n_1 \, d_1^3 = n_2 \, d_2^3 \qquad (14.1)$$

if $d_2 = d_1/2$, so

$$n_1 \, d_1^3 = n_2 \, d_1^3 / 8 \qquad (14.2)$$

and $n_2 = 8 \, n_1$, the contact area for both cases will be as follows

$$A_1 = n_1 \, d_1^2 \qquad (14.3)$$

$$A_2 = n_2 \, d_2^2 = n_2 \left(\frac{d_1}{2} \right)^2 = 2 \, n_1 \, d_1^2 = 2 \, A_1 \qquad (14.4)$$

Thus, the contact area doubles when the droplet diameter goes half.

The study of sprinklers/hot layer interaction made by Heskestad, Gunnar, 1991 at the Mutual Factory Research Corporation, Boston, USA shows the following. The model based on the two-layer zone model and 25 tests with sprinkled room fires shows that:

- the water drops contribute significantly to evaporation and cooling in the hot layer and are in the thermodynamic equilibrium with the environment, i.e. all heat transferred to the drops is absorbed in vaporising drops,
- the effective cooling diameter of the drops in the spray was indicated at 70% of the volume mean diameter,
- ratio heat absorption of spray Q_s contra actual heat release rate Q_a was about 0.5 for 11.1 mm diameter sprinkler at the discharged rate of 68.2 l/min. Some numbers for it are presented in the Table 14.1. These parameters were chosen as the most usual sprinkler parameters.

Table 14.1   Conditions for tests presented in Heskestad, Gunnar, 1991.

Test No.	D (mm)	V_w (l/min)	Q_a (kW)	Q_s (kW)	Q_s/Q_a	T_a K
15	11.1	68.2	137	75.9	*0.55*	297
19	11.1	68.2	282	134.8	*0.48*	301
23	11.1	68.2	460	229.6	*0.50*	304
24	11.1	68.2	474	240.6	*0.51*	301

where

D nozzle diameter;

V_W volumetric water discharge rate of spray nozzle;

Q_a actual heat release rate;

Q_s heat absorption rate of spray;

Q_s/Q_a ratio heat absorption of spray Q_s contra actual heat release rate Q_a;

T_a temperature of ambient air.

With a certain uncertainty one can assume that the ratio heat absorption of spray is 50% of the actual heat release rate.

The fractional change in droplet diameter is proportional to 1/3 power of the decrease of mass. A reduction of the droplet mass by evaporation to one half of its original value will reduce the droplet diameter by only 20%.

It seems to be important to notice that both of above presented studies examined the cooling effect for only one sprinkler of different types and diameters under steady-state conditions. The model in both studies assumes two-zone model with hot upper and cool lower layers of uniform temperatures and no direct interactions with a fire plume.

Another phenomenon due to the cooling effect of sprinklers on the ambient air and smoke is a reversed flow through smoke vents as a result of the indoor temperature being somewhat lower than the outdoor temperature. This can be expected during spring/summer. This can cause backflow through smoke vents.

The most common way to assess conditions causing this phenomenon is as follows. To prevent smoke backflow, an empirical equation limiting air velocity between two spaces is recommended by Heskestad (1989):

$$v = C \sqrt{\frac{g H (T_f - T_o)}{T_f}}$$

(14.5)

where

v average air velocity, m/s;
H height of opening, m;
g acceleration of gravity, m/s^2;
T_f temperature of heated smoke, K;
T_o temperature of ambient air, K;
C contraction factor=0.64.

This equation is the empirical correlation and is carried out for vertical opening and, hence, is unsuitable for horizontal openings like smoke vents.

As it was presented in Gordonova P. (1998), the maximum expected fire flow is a function of the volume of the space studied. Hence, both fire flow and fire pressure are limited by the space volume. This is correct for unsprinklered fires. For sprinklered fires maximum fireflow produced by the fire is limited by the temperature of sprinklers activation. For steady fires this temperature can be estimated by Alpert equation, that yields:

$$\Delta T = \frac{5{,}38 (Q/r)^{2/3}}{H} \qquad\qquad r/H > 0{,}18$$

(14.6)

where

r radial position, m;
H ceiling height above fire source, m;
Q heat release rate, kW;
ΔT temperature difference between smoke layer temperature and ambient temperature, K.

This equation shows that temperature difference is a function of height, not the volume of the space. This temperature difference applied on the fire simulation model for t^2-fires means certain uncertainty. Some fire simulation with two-zone model and integrated temperature difference according to Alperts equation were made. The fire flows generated by these fires were analysed with the MINITAB-program (MINITAB, 1988). The resulting regression analyses on fire flows as a function of height and volume of the studied spaces showed poor agreement with the coefficient

of determination of approximately 92%. The main purpose of this evaluation was to assess fire flow produced by unsprinklered fire contra sprinklered fires in the same spaces. The right answer could be expected in large spaces, where the temperature difference activating sprinklers occurs before the maximum fire flow could be expected otherwise (before lack of oxygen occurs).

Due to lack of studies comprising all variables effecting the phenomenon the correct result can hardly be estimated. The problem seams to be a rather complicated one and more research obviously is needed.

14.1   Improving the function of smoke vents with the help of sprinklers

Possibility of improving the smoke extraction function of a vent with the help of ejecting water flow (spray) from a sprinkler is examined in this subchapter. Sprinkler in this case can be of a special design and straighten upwards.

Commonly, sprinklers can be installed upwards, downwards or can be arbitrarilly straightened. A common phenomenon of a downward straightened sprinkler is that it pulls down air and smoke towards the floor by the action of the water droplets due to the momentum. Airflow increases with increasing distance from the sprinkler. Flow from a sprinkler, its initial velocity and drop diameter affect airflow.

Sprinkler diameter and flow determine initial droplet velocity (the ordinary initial velocity is about 10 m/s). This velocity diminishes essential by slowing down of sprinklers distributor. After this drop velocity reduces somewhat and becomes constant in proportion to the airflow velocity rather quickly. This difference in velocities is equal to droplet velocity for a free fall that is a function of drop diameter. Initial drop velocity is, hence, of less importance because of the fact that drop velocity becomes equal to a free fall velocity rather quick. Airflow is, thus, determined by water flow, sprinklers distribution and the vertical distance under the nozzle.

The problem with upward straightened sprinklers is that airflow slows down and stops at some range due to gravity. Water drops fall down through this upward going airflow. In the case of airflow/sprinkler droplet interaction above the roof level, wind can also affect the phenomenon.

A simple estimation of energy required for driving water spray upwards is presented in Jensen Lars, 2002. Analysis has shown that airflow velocity diminishes with increasing spray ejection. Comparison of drop velocity with the air flow velocity through a roof mounted smoke vent has shown that for air flow velocities exceeding 5 m/s the ejector force of sprinkler spray straightened upwards can be neglected. This statement makes the expected advantage of this method even less interesting. Momentum exchange calculations have shown the same result.

A model for friction between spray drops and air has been used. Three different spray directions have been examined: upwards, downwards and horizontal. Twenty-seven calculations with different combination of three variables: full-cone spray angle, spray flow and direction are presented. Results show that upward straightened spray has relatively short ranges and airflow. Drops slow down at distances less than 1m. Analysis did not take into account drops falling down. This means that the presented results for the upward straightened sprays are overestimated.

High initial spray velocities are essential for achieving high airflow because of the ejecting. In the ordinary sprinklers the resulting drop velocity is moderate and usually does not exceed 5 m/s. A solution could be a special designed sprinkler or an ordinary sprinkler without distributor.

To sum up the results of the study, the smoke evacuating function of a smoke vent can hardly be improved with the help of using upward straightened sprinkler.

15 Maximum temperature of different ventilation fans, ventilation ducts and ventilation systems

The ability of a ventilation system to evacuate fire gases is limited by its own maximum service temperature. The problem is more characteristic for exhaust systems (fans) then for supply systems because of the delusion of hot air. The problem can be divided into two major issues: maximum temperature of ventilation ducts and maximum temperature of ventilation fans. The problem is that the motor and the belt can be placed inside the ventilation plant and therefore can be cooled down by the same air flow that is transported by the fan itself.

The following analysis is the summary of two reports on the issue of Lars Jensen: Lars Jensen, 1998. "Ventilationssystemets uthållighet vid brand", Rapport TABK--98/7046, Lund University (in Swedish) and Lars Jensen, 1999. "Elmotorers uthållighet vid höga temperatur", Rapport TABK--99/7056, Lund University (in Swedish).

15.1 Maximum temperature of ventilation fans

Three different cases are possible regarding fans lifetime:

1. The simplest case, when increased temperature is less then that prescribed for the fan;

2. Increased temperature is beyond boundary permitted parameters without direct damage of the fan, but it shorts its lifetime considerably;

3. Fan goes broken during abnormal operation.

Fire loads time is much shorter then fans lifetime. Fire resistance time defined for buildings is applied to ventilation system also.

The most sensitive parts of a fan are the motor winding, bearing and belt. Hence, winding, ball bearing and belt determine thermal endurance of a fan.

15.1.1 Ball bearing

Usually, bearings normal operation temperature is approximately 10-15°C higher then surrounding temperature. Steel changes its characteristics after one-month exploitation at 150°C and after only four hours at 350°C. Seal protects bearing against external contamination and keeps grease. Seal consists of nitric rubber, which sets the limits for temperature rise to 160°C.

Greases temperature limits do not exceed 130°C.

Ball bearing should stand temperature of 200°C during at least 120 min for the highest fire resistance.

15.1.2 Belt

Usually, a belt should stand normal operation at 80°C external temperature. A belt operating at 150°C is estimated to stand during maximum 10 hours. Operation at 200°C is considered to be impossible because rubber vulcanises once more time and becomes fragile.

15.1.3 Motor

Ordinary motors are classified to operate at 40°C. The most sensitive part of a motor is insulation of windings. Threads are covered with lacquer. Their thermal resistance manages up to 300°C. Special materials separating windings manage between 130 and 160°C ambient temperature.

A motor can be fabricated with different insulation in order to manage different high winding temperature caused by high ambient temperature. The highest permitted windings temperature varies between 105°C and 180°C.

Hence, winding determines thermal endurance of a motor.

15.2 Exhaust airflow temperature and thermal endurance of a motor

Report examines different parameters, which are important for thermal resistance and, hence, for lifetime of a fan:

- ambient temperature;
- exhaust airflow temperature;
- power demand as a function of temperature;
- static thermal endurance of a motor and
- dynamic thermal endurance of a motor.

The problem of thermal endurance of a motor is examined with the help of three models: at constant mass airflow, at constant volume airflow and at constant pressure drop.

The analysis is based on the fact that power demand of a motor/fan is indirectly affected by the temperature depended air density and that fans thermal endurance is influenced directly by the temperature of the ambient air.

Analysis with constant mass airflow through the fan results in an overestimate because under constant mass airflow conditions density is halved and velocity doubles when temperature doubles.

Under constant volume airflow conditions the mass airflow from the fire room is underestimated because density and therefor mass airflow, as well as pressure, are halved when temperature doubles.

Analysis of the problem based on constant pressure drop assumes that ρv^2 is similar both for an ordinary operation and in case of fire. Model tests a two-branch exhaust ventilation system with different ratio of airflow from fire room (0.2 – 0.5) and for fire airflow of 738, 841, 945 and 1 049°C, which corresponds to four different fire resistance classifications.

Exhaust airflow temperature is always less then 128°C for the fire flow ratio up to 0,2 with fire airflow temperature of 1 049°C according to the highest fire resistance classification.

Exhaust fire flow with ratio of 0.3 does not exceed temperature limit of 192°C.

Fire flow ratios of 0,4 and 0,5 mean that approximately half of the building is burning, that is an extreme case.

Pressure produced by an uncontrolled fan with a constant number of revolutions is proportional to air density and inverted proportional to temperature. Volume airflow does not change because pressure drop is also proportional to density.

A pressure-controlled fan means that parameter ρv^2 is also constant because pressure drop in ducts is also proportional to ρv^2.

An air volume controlled fan can be regulated according to changing in dynamic pressure ρv^2, which is the same as for a pressure-controlled fan. Required effect, P, is proportional to ρv^3 and, thus, increased temperature results in less density of the airflow and increased velocity as well as in increased effect. Following connection is valid for pressure- and air-volume controlled fans: $P \sim \rho v^3 \sim V \sim \rho^{-0.5} \sim T^{0.5}$.

Ordinary permitted windings temperature at nameplate power ratings is approximately 70°C higher then ambient temperature. It means that there is some margin to the highest permitted winding temperature and therefore it can be raised to 155°C and 180°C for surrounding temperature of 85°C and to 110°C respectively.

Winding temperature is determined by the power of the motor. A motor with at nameplate power ratings can therefore manage higher ambient temperature. All motors are classified to manage 40°C ambient temperature. Some more values are presented in Table 15.1

Table 15.1   Changed power of a motor according to different ambient temperatures, °C.

Ambient temperature, °C	Relative power of the motor
30	1.07
40	1.00
50	0.93
60	0.865
70	0.79
80	0.70

As it is seen from the Table 15.1 decreased relative power of the motor (0.7) manage ambient temperature of 80°C. Thus, a motor can manage 40°C higher ambient temperature and therefore have 40°C lower winding temperature then ordinary one at nameplate power ratings.

Inner temperature of a motor can be according to the Table 15.1 simplified and described as a lineal function of the relative power of the motor, p_r, as follows

$$T_m = T_f + 70 - (40/0.3)(1 - p_r) \qquad °C \qquad (15.1)$$

The relative power of the motor, p_r, depends on the surrounding temperature.

For uncontrolled ventilation fan it results in reduction of required fan power at increasing ambient (exhaust airflow) temperature.

For controlled ventilation fan it results in lower allowed exhaust airflow temperature compared to unregulated fan along with higher then one relative power of the motor, p_r.

Hence, allowed highest ambient air temperature is much more limited for controlled ventilation fan because the fan is in directly controlled by the dynamic pressure.

Lifetime analysis presented in Lars Jensen, 1998, show connection between windings temperature and lifetime. According to this, winding is expected to manage 190°C ambient temperature for at least 10 hours. At the same time, corresponding windings temperature is approximately 260°C. It means that motors lifetime should be longer then belt's lifetime.

Ordinary measures protecting motor against overload do not work in the fire case because power of the fan decreases for uncontrolled fans. There is, however, certain risk for overload for pressure- and airflow controlled fans.

15.3   Dynamic temperature endurance of a motor

A motor can manage short periods of time with temperature overload on condition that inner temperature of a motor is beyond certain temperature limits for materials used. This is possible because a motor ordinary works with a certain temperature margin. A simplified dynamic model for evaluation of these margins is presented in Lars Jensen, 1998. The model describes inner temperature of motor as a function of equilibrium temperature and motors thermal characteristics.

Results show that time lag of a motor increases along with increasing motor size and temperature endurance of a motor is directly proportional to time lag of a motor.

Theoretical results showed good agreement with experiment results presented in Gunnar Kylander, 1995.

15.4 Motors thermal endurance

In order to examine thermal endurance of motors three motors were tested at the Department of Fire Safety, Lund University of Technology. Description and results of this study are presented in Lars Jensen, 1999.

Table 15.2   Data on the motor examined (EEx e II T3, ABB Motor).

Parameter	Unit	
Motor power	kW	1.3
Efficiency	-	0.8
Nameplate current	A	2.9
Mass	kg	13

The idling case was studied. Motors inner temperature is somewhat less then that for an ordinary operation because power loss is less with idling. All tests showed that operation could be maintained during limited time with winding temperature of approximately 300°C. Endurance/time from start (both cold and warm) of the motor to the point, when winding temperature reaches 300°C, is presented in Table 15.3.

Table 15.3   Motors endurance at different ambient temperatures

Temperature, °C	Durability, min	
	Cold start	Warm start
200	∝ (291 °C)	∝ (291 °C)
250	50	43
300	34	27
350	24	19
400	19	16

Ambient temperature at which winding temperature reaches 300°C at certain time intervals from start (both cold and warm) of the motor is presented in Table 15.4.

Table 15.4   Ambient temperature at given motors endurance

Endurance, min	Ambient temperature, °C	
	Cold start	Warm start
15	445	395
30	309	282
60	234	226
120	212	212
240	211	211

At ordinary operation and ordinary axle load rotor temperature expected could be higher then winding temperature, but rotor is short-circuited and, thus, is assessed to have high thermal endurance.

Ball bearing managed over 250°C for several hours.

Axle seal managed over 250°C and became somewhat fragile.

Motor cooled fans and their air inlet plastic cover melted totally at 160°C. It could be to advantage if ambient air is warmer then cover temperature, and it could be to disadvantage, if opposite.

15.5 Summary

Air temperature influences exhaust ventilation systems fans indirectly through the changing density of the airflow and hence, affecting power required, and directly affecting thermal resistance of the fan. Higher temperature of exhaust airflow diminishes required power of the fan and at the same time shortens down lifetime.

Evaluation of thermal endurance of exhaust ventilation system (Lars Jensen, 1999) showed that an unregulated fan with a belt stands 150°C ambient temperature for maximum 10 hours. This is much longer then that required for highest fire resistance classification (120 min). An axial fan is better then a centrifugal in this regard. Pressure- and air volume-controlled fans can diminish the highest permitted operation temperature because of the increasing power demand and temperature increase can, if the worst increase the motor loading the power.

The fact that a fan stands certain fire load does not mean that its parts, such as motor or belt, remain undamaged.

Motors thermal time lag is often shorter then 40 min and operation during 120 minutes means that stationary state attains and there is no need of a dynamic analysis.

Exhaust airflow temperature according to the Table 15.2 is always less then 128°C with fire flow ratio up to 0,2 and temperature of 1 049°C (according to the highest fire resistance classification).

Temperature limit of 192°C does not exceed for fire flow ratio of 0,3.

Fire flow ratio of 0,4 and 0,5 mean that approximately half of the building is burning, that is an extreme case.

An assumed simple connection between relative motors power, ambient temperature and inner motor temperature (equation 15.1) is quite uncertain. Motors overheating temperature disappears at the relative motor power of 0.475. Only idling causes overheating of motor with 30°C.

15.6 Maximum temperature of different ventilation ducts

The most frequently used material in ducts in industrial buildings is galvanized steel. The base metal is hot-rolled or cold-rolled steel. Different coatings may be used sometimes: zinc, aluminum-zinc alloy, aluminum, polyvinyl chloride (PVC) and fiber-reinforced (FRP). In some chemistry industries stainless steel is used and in swimming pools aluminum ductwork could be found. Cold-rolled copper ducts are not so usual, but occasionally they are used in i.e. lobbies and atria. The above-presented cases do not cover the whole range of the ventilation duct's materials used. Data concerning maximum prescribed service temperatures for some of materials mentioned here is presented in the Table 15.5. This temperatures are prescribed by the American Standards, ASTM, (and by the comparable ISO 3575), and Swedish Standards SS.

Table 15.5   Prescribed service temperatures for different ventilation duct materials according to American Standards, ASTM, and Swedish Standards, SS.

No	Type of material	Maximum service temperatures, °C		Diverse
		According to ASTM	According to SS	
1	Steel	121	120	Usual
2	Hot-rolled and cold-rolled steel	343	300	For industrial use without stress
3	Zinc coated steel	204	200-250	
4	Aluminum coated steel	482-538	315	Discoloration occurs over 428°C
5	PVC and FRP coated steel	65-93	60	
6	Stainless steel	427	500-700	
7	Aluminum	204	200-300	Aluminum becomes softer after two years operation at 200°C
8	Copper	unknown	300°C	

16 Discussions and conclusions

Introduction

The theoretical studies and computer simulations have provided knowledge regarding smoke evacuation from large spaces with the help of different measures in combination with the use of ordinary ventilation systems. Application of this basic knowledge totally depends on the internal pressure in the building. This internal pressure is a function of different factors.

Smoke management can be interpreted as successful smoke venting from a space effected by different factors in the fire case. These factors are:

- wind pressure around the whole building (the roof included);
- buoyancy due to temperature difference;
- fire expansion;
- ventilation fan pressure and
- sprinklers.

The model created and presented here takes into account all these factors and provides a means of analyzing pressure distribution and resulting flows in/out of the examined space.

All combinations of theoretically possible smoke management measures such as opening of smoke vents and openings for make-up air, running roof mounted smoke fans along with running ordinary ventilation systems are embraced by the presented model.
Results of the studied cases are described in terms of right/wrong function of the smoke vents. This phenomenon is the prevalent parameter for the present study.

The study is interdisciplinary and comprises different fields of knowledge: fire protection engineering, building science and building services.

Computer programs

SIMNON is a computer program for the simulation of mathematical, non-linear relationships between the input and output signals in a system, as well as integration of several dynamic subsystems into one total system. Simnon is made by SSPA Systems, a group within SSPA Maritime Consulting AB. The program was used in evaluating different models, e.g. pressure rise due to expansion.

For the purpose of evaluating smoke evacuation through roof vents and roof mounted fans, a computer program PFS was used. This program, developed and written by Lars Jensen, is based on the semi graphical circuit drawings and treats arbitrary flow systems of any structure and layout, any media, and any problem: design or investigation. The program manual for PFS includes six major reports and four reports with applications (Lars Jensen, 1995, 1996).

Fire scenario and fire size

With reference to all information on possible fire scenarios in large spaces presented in different sources and due to the absence of specific heat release rate data, it was assumed that the design fire is steady. A steady fire has a constant heat release rate as a result of limitations of fuel and combustion air. Due to the fact that such fires result in somehow overestimated ventilation rates in comparison with unsteady fires, this idealization results in parameters on the safe side.

In this study the design fire size is assumed to have a heat released rate of 5 MW. For several estimations other fire sizes were also examined: 2.5 MW and 25 MW.

Buoyancy

The difference in pressure between the hot smoke layer and the outside at ceiling level, as it is well known, is a function of smoke layer depth, temperature difference between hot smoke layer temperature and ambient air temperature. Some pressure values characteristic for ordinary large spaces at different smoke temperatures are evaluated. The maximum theoretically possible buoyancy never exceeds 12 Pa/m.

Pressure rise due to expansion

Pressure rise due to expansion can become a determining factor in indoor pressure assessment. The usual way to evaluate this parameter is based on the assumption that rate of temperature rise, B (K/s), is constant. As a matter of fact it is a function of temperature rise. A pressure rise model was construsted and some results of computer simulations with the program SIMNON are presented. Both steady and t^2- fires are tested. The results show some difference between two models.

Airtightness in industrial buildings

Validation of the magnitude of internal and external leakage paths in the studied spaces is an important issue for evaluation of both fire development in the room and predicted parameters.

The study of relevant literature both in Sweden and abroad has shown that the air leakage rate according to Swedish Building Regulations BBR (6 m^3/h,m^2 for other buildings than dwellings), applied to the whole building envelope, can be accepted as a suitable and probable value for Swedish industrial buildings. The corresponding air leakage in industrial buildings in the USA is 60 m^3/h, m^2 relating to the area of the building envelope. This case has also been examined.

The analysed data is not sufficient, as it does not cover all possible combinations of leakage area with the mean age of the buildings.

Equivalent indoor wind factor

In order to evaluate indoor pressure as a function of the external wind pressure on building surfaces under different conditions, a model was constructed. The combination of wind pressure on a building and the airtightness of the building along with opening of doors, windows in the walls and fire vents on the roof can give rise to great variations in pressure. The resulting indoor pressure can be defined as a function of dynamic wind pressure multiplied by some resulting indoor wind factor. This indoor wind factor was defined here as an equivalent indoor wind factor.

131

In order to evaluate indoor pressure as a function of the resulting equivalent indoor wind factor, a model was constructed. The model can solve the problem analytically for two surfaces (n=2); in other cases numerical methods have to be used.

The more complicated cases with different areas of openings on the windward and/or leeward sides of the space and the roof are analyzed with the help of the computer program PFS.

Design parameters

For the purpose of this study design parameters were estimated. These parameters include space examined, weather data, fire and smoke layer characteristics, and values for ventilation systems.

The study was made for the space of 100x100x10 m^3 with total evenly distributed air leakage area of 3.5 m. The design roof was of arbitrary type with windward side wind factor μ = 0.2 and leeward side wind factor μ = -0.2.

Outdoor temperatures of -20°C, 0°C and 20°C are chosen for this study. Extreme wind velocity of 25 m/s is chosen as the max reference wind velocity. Along with these extreme parameters, the more usual temperature of 0°C and wind velocities of 5 and 10 m/s were also tested.

The design fire is a steady fire with heat release rate (RHR) of 5 MW.

The design smoke layer with depth of 6 m has temperature of 400°C and buoyancy of 36 Pa.

Ventilation fans are as follows:

supply fan - 60 m^3/s at 444 Pa;
exhaust fan - 60 m^3/s at 444 Pa and
smoke fan - 10 m^3/s at 60 Pa.

Study of cases

An analysis of the schematic models, evaluation of the wrong/right function of smoke vents in the studied space with/without fire and with working/non-working ordinary ventilation systems is presented in this study. These cases were analyzed with the help of the computer program PFS.

The study was made "step-by-step":

- "cold" case without ventilation (indoor temperature 20°C),
- fire case with some ventilation imbalance (smoke layer temperature 400°C),
- fire case with either supply or exhaust ventilation system in operation (smoke layer temperature 400°C),
- real fire case with the ordinary supply-exhaust ventilation system along with variations in the opening of the smoke vents and/or roof mounted smoke fan (smoke layer temperature 400 °C).

The study comprises up to thirteen cases of variation in smoke/inlet vent opening along with additional variations in studied cases.

Cooling effect of sprinklers

The obvious dependence of inner parameters on sprinkler operation and the resulting operation of smoke vents should be described in numerical terms based on theoretical grounds. The series of different studies had the aim of elucidating the influence of smoke venting on the operating characteristics of sprinklers. Apart from that, the theoretical basis for such evaluations can hardly be considered as sufficient. The attempt was made to evaluate the problem inversely. The cooling effect of sprinklers lowers temperature of ambient air, as the smoke layer mixes with the rest of the air due to the absence of temperature difference. The rate of heat absorption by the spray and, hence, the heat which remains to warm the ambient air could be assessed according to some results of the study presented in Heskestad, 1991. According to this study, the ratio of absorption by the spray can be assumed to be 50%. It should be noted that the study was made for only one spray and under very special conditions with forced direction of airflow out of the box tested. The problem of backflow, if any, through smoke vents due to reverse temperature difference over the opening could not be solved with the help of the equation proposed for the vertical opening between two spaces.

Regression analyses made on the fire simulation results regarding fire flow showed poor agreement. This could be partly explained by integration of Alpert's equation for steady fires on the t^2-fires and by the insufficient number of spaces tested.

Improving the function of smoke vents with the help of sprinklers

Commonly, sprinklers can be installed upwards, downwards or can be arbitrarily straightened.

The problem with upward straightened sprinklers is that airflow slows down and stops at some range due to gravity. Water drops fall down through this upward going airflow. In the case of airflow/sprinkler droplet interaction above the roof level, wind can also affect the phenomenon.

Analysis has shown that airflow velocity diminishes with increasing spray ejection. Comparison of drop velocity with the air flow velocity through a roof mounted smoke vent has shown that for air flow velocities exceeding 5 m/s the ejector force of sprinkler spray straightened upwards can be neglected. This statement makes the expected advantage of this method even less interesting.

Momentum exchange calculations have shown the same result.

A model for friction between spray drops and air has been used. Three different spray directions have been examined: upward, downward and horizontal. Results show that an upward straightened spray has relatively short ranges and airflow. Drops slow down at distances less then 1m. Analyses did nor take into the account drops falling down. This means that the results presented for the upward straightened sprays are overestimated.

High initial spray velocities are essential for achieving high airflow because of the ejection. In the ordinary sprinklers the resulting drop velocity is moderate and usually does not exceed 5 m/s. A solution could be a specially designed sprinkler or an ordinary sprinkler without a spreader plate.

To sum up the results of the study, the improvement in the smoke evacuating function of a smoke vent due to an upward straightened sprinkler is negligible.

Maximum temperature of ventilation systems

The ability of a ventilation system to evacuate fire gases is limited by its own maximum service temperature. The problem can be divided into two major issues: maximum temperature of ventilation ducts and maximum temperature of ventilation fans. The problem is that the motor and

belt can be placed inside the ventilation plant and therefore can be cooled down by the same airflow that is transported by the fan itself. The maximum temperature of ventilation fans depends on the thermal endurance of its components: ball bearing, belts and motor itself. An evaluation of possible maximum operating temperatures for different parts of a fan is presented.

Exhaust airflow temperature and thermal endurance of a motor

The problem of thermal endurance of a motor is examined with the help of three models: constant mass airflow, constant volume airflow and constant pressure drop. Different parameters that are important for thermal resistance and, hence, for the lifetime of a fan are also taken into account: ambient temperature, exhaust airflow temperature, power demand as a function of temperature and static thermal endurance of a motor.

The analysis is based on the fact that the power demand of a motor/ fan is indirectly affected by temperature dependent air density and that the fan's thermal endurance is influenced directly by ambient temperature.

The relative power of the motor depends on the ambient temperature.

For an uncontrolled ventilation fan this results in a reduction in required fan power at increasing ambient (exhaust airflow) temperature.

For a controlled ventilation fan it results in a lower allowed exhaust airflow temperature compared with an unregulated fan, along with higher than one relative power of the motor, p_r.

Hence, the highest allowed ambient air temperature is much more limited for a controlled ventilation fan because the fan is indirectly controlled by the dynamic pressure.

A lifetime analysis presented in Lars Jensen, 1998, shows the connection between winding temperature and lifetime. According to this, the lifetime of the motor should be longer than the belt's lifetime.

Ordinary measures protecting the motor against overload do not work in the event of fire because the fan power decreases for uncontrolled fans. There is, however, a certain risk of overload for pressure- and airflow controlled fans.

In addition to analytical evaluations of the problem some results from the examination of the thermal endurance of three motors that were tested at the Department of Fire Safety, Lund University of Technology, are presented in the report.

Maximum temperature of different ventilation ducts

The maximum temperature of different ventilation ducts depends on the duct's material and the coating used. An evaluation of this for some commonly used materials is presented in the study.

Application

The model presented can be used to evaluate the effectiveness and area of roof vents in comparison with the ordinary ventilation system. This can be evaluated step-by-step with the help of computer programs as follows:

step 1   the space studied is described with the help of a computer program,

step 2   any smoke vents and make up air openings are described in the created model,

step 3   the fire flow is evaluated,

step 4   the characteristic of dangerous wind velocities are estimated,

step 5   the ventilation system studied is described with the help of a computer program,

step 6   the model studied is tested for fire smoke evacuation.

The results can be analysed in terms of fault (reversed) airflow direction or in greater detail as numerical values of flows in/out of the studied space.

Different measures for reducing the undesired (reversed) airflow through the roof vents, such as the ordinary ventilation system(s) in operation and/or smoke fans instead of smoke vents could then be tested.

Important results

The most important result is the method produced in the study. This method is a simple tool to evaluate the optimum combination of different measures for smoke management that is best for the particular space located at the particular site. As a result of this analysis ordinary ventilation systems operating along with optimum airflow through the roof mounted smoke fan or the optimum area and siting of the smoke vents could be determined.

A motor manages maximum 180°C and the motor's thermal time lag is shorter than 40 min. Exhaust airflow temperature is always less then 128°C with fire flow ratio up to 0,2 and temperature of 1 049°C (according to the highest fire resistance classification). In extreme cases motors manage temperatures exceeding 250°C for several hours. This does not mean that they remain undamaged.

Fans without control manage ambient temperature of 150°C for at least 10 h. This is a much longer time than that required by the highest fire classification (2 h).

On the whole, the best results regarding smoke evacuation efficiency occur with a working supply ventilation system and a shut down exhaust ventilation system regardless of the type of smoke evacuating measures. Hence, the combination of working supply fan along with different combinations of smoke evacuating measures can be considered as an effective measure. Supply ventilation outlets are supposed to be placed near the floor.

Sprinklers influence the effectiveness of smoke management due to their cooling effect on the ambient air.

Future research

Owing to some uncertainty in the assumptions made, the paucity of experimental data and lack of knowledge regarding certain fire processes, sprinkler influence and wind data, it seems to be necessary to investigate the problem further.

The fire scenario in the buildings studied, with characteristic burning items involved, is of interest. Such "real" fires can produce fireflows different from those predicted in this work.

The possibility of using ordinary ventilation systems along with other safety measures (smoke venting, sprinklers, etc.) in the event of fire in such buildings can improve safety, and the economic consequences of this are far from negligible.

The problem of sprinkler influence on the operation of smoke vents must be studied in greater detail. This matter needs further research.

The results of the problem studied predict the operation of smoke vents in terms of right/wrong airflow through these. As a matter of fact, the resulting parameters obtained from simulations are airflow, pressure and pressure loss, and airflow direction through a smoke vent. This fact provides a greater opportunity for further and more detailed analysis of pressure versus airflow conditions in a certain studied space.

It seems necessary to investigate the results further in numerical terms.

References

ASHRAE Handbook, (1997). Fundamentals, SI Edition, ISBN: 1-883413-72-9 USA.

ASHRAE Handbook (1999). Heating, Ventilation and Air-Conditioning Applications, SI Edition, ISBN: 1-883413-45-1 USA.

BBR 94. (1993). Boverkets Byggregler, Foreskrifter och allmänt råd, BFS 1993:57, Boverket (in swedish).

BOCA (1993). The BOCA National Building Code. Country Club Hills, IL: Building Officials & Code Administrators International, Inc.

Brand&Räddning NR 6-7 1997, NR 6-7 1998 (in Swedish).

Brand&Räddning NR 7 1999 (in Swedish).

Degenkolb, J.G. (1975). Fire safety for atrium type buildings. *Building Standards* 44: 16-18.

Degenkolb, J.G. (1983). Atriums. *Building Standards* 52: 7-14.

Dillon, M. E. (1994). "Determining effectiveness of atria smoke control systems", *ASHRAE Journal*, April 1994.

Elmroth, A. (1985). "Energisnåla stålhallar, Byggnadstekniska lösningar för god lufttäthet och effektiv värmeisolering", SPI-publikations 95 – 1985 (in Swedish).

Elovitz, D. M. (1996). "Evaluating smoke control and smoke management systems", *ASHRAE Journal*, March 1996.

Elovitz, K. M. & Elovitz, D. M. (1993). "Understanding smoke management and control", *ASHRAE Journal*, April 1993.

Gordonova, P. (1998). *"Spread of Smoke and Fire gases via the Ventilation System"*, Report TABK--97/1011, Lund University, Lund Institute of Technology, Department of Building Science, Sweden.

Heskestadt, G. (1984). Engineering relations for fire plumes, *Fire Safety Journal* 5(2):109-114.

Heskestadt, G. (1991). "Sprinkler/Hot Layer Interaction", NIST-GCR-91-590, National Institute of Standards and Technology.

ICBO. 1994. The Uniform Building Code. Whittier, CA: International Conference of Building Officials.

Jensen, L. (1993). *"Spridning av rök och brandgaser i ventilationssystem"*, Rapport TABK--93/3011, Lund University (in Swedish).

Jensen, L. (1995a). "Beskrivningsspråk för PFS", Rapport TABK--95/7020, Institutionen för byggnadskonstruktionslära, LTH, Lund (1995) (in swedish).

Jensen, L. (1995b). *"Beräkningsuttryck för PFS"*, Rapport TABK--95/7022, Institutionen för byggnadskonstruktionslära, LTH, Lund (1995) (in swedish).

Jensen, L. (1995c). *"Tillämpningsexempel med PFS"*, Rapport TABK--95/7023, Institutionen för byggnadskonstruktionslära, LTH, Lund (1995) (in swedish).

Jensen, L. (1995d). *"Brandtekniska beräkningar med PFS"*, Rapport TABK--95/7024, Institutionen för byggnadskonstruktionslära, LTH, Lund (1995) (in swedish).

Jensen, L. (1995e). *"Brandtekniska övningsexempel med PFS"*, Rapport TABK--95/7025, Institutionen för byggnadskonstruktionslära, LTH, Lund (1995) (in swedish).

Jensen, L. (1996). *"Arbetsbänk för PFS"*, Rapport TABK--96/7033, Institutionen för byggnadskonstruktionslära, LTH, Lund (1996) (in swedish).

Jensen, L. (1998). *"Ventilationssystemets uthållighet vid brand"*, Rapport TABK--98/7046, Lund University (in Swedish).

Jensen, L. (1999). *"Elmotorers uthållighet vid höga temperatur"*, Rapport TABK--99/7056, Lund University (in Swedish).

Jensen, L. (2002). *"Förbättrad brandgasventilation med hjälp av sprinkler"*, Rapport TABK--02/7065, Lund University (in Swedish).

Klote, J. H. (1997). "Prediction of smoke movement in atria: part I and II", ASHRAE Transactions: Symposia, BN-97-5-2, 3.

Klote, J. K., & Milke, (1992). "*Design of smoke management systems*". Atlanta: American Society of Heating , Ventilation and Air-Conditioning Engineers, Inc.

Kylander, G. (1995). "Thermal modelling of small cage induction motors". Chalmers University of technology, Department of Electrical Machines and Power Electronics, Technical Report No. 265.

Lougheed, G. D., & Hadjisophocleous, G. V. (1997). "Investigation of atrium smoke exhaust effectiveness", ASHRAE Transactions: Symposia, BN-97-5-1.

Lui, S.T. (1977). Analytical and experimental study of evaporative cooling and room fire suppression by corridor sprinkler system. NBSIR 77-1287. Gaithersburg, Md.: National Bureau of Standards (now NIST).

Lundin L. I. (1986). "Air leakage in industrial buildings – description of equipment". Measured Air Leakage of Buildings, ASTM STP 904, H.R.Treschel and P.L. Lagus, Eds., American Society for Testing and Materials, pp. 101-05.

Minitab Handbook, (1988). Second Edition. Boston, Minitab Inc.: PWS Publishes (1988).

Persily, A. K. (1999). "Myths About Building Envelopes", *ASHRAE Journal*, March 1999.

RUS 120:4. Regler för automatisk vattensprinkleranläggning, FSAB Försäkringsbranschens Serviceaktiebolag, 199? (in Swedish).

Simnon for Windows, version 1.0, May 1993. SSPA Systems, Box 24001 400 22 Göteborg, Sweden.

"Snö och vindlast", Utgåva 2, Boverkets handbok om Snö och vindlast, BSV 97, BOVERKET 1997 (in Swedish).

Stratton, J. H. (2000). "Metal Duct Selection And Application", *ASHRAE Journal*, June 2000.

Tamura, G.T. (1995). *Smoke movement and control in high-rise buildings*. Quincy, Mass.: National Fire Protection Association.

Tanaka, T., & Yamana, T. (1985a). "Smoke Control in Large Scale Spaces (part 1: Analytic Theories for Simple Smoke Control Problems)". Building Research Institute, Ministry of Construction, Japan, July, 1985.

Tanaka, T., & Yamana, T. (1985b). "Smoke Control in Large Scale Spaces (part 2: Smoke Control Experiments in a Large Scale Space)". Building Research Institute, Ministry of Construction, Japan, July, 1985.

The SFPA Handbook of Fire Protection Engineering, 2nd edition, ISBN: 0-87765-354-2, USA (1995).

William, A., & Webb, P. E. (1995a). "Development of Smoke Management Systems", *ASHRAE Journal*, April 1995.

William, A., & Webb, P. E. (1995b). "Development of smoke management systems", *ASHRAE Journal*, August 1995.

LUND INSTITUTE OF TECHNOLOGY
Lund University