International Energy Agency

# Ventilative Cooling Sourcebook

## Energy in Buildings and Communities Programme

## March 2018

EBC is a programme of the International Energy Agency (IEA)

Front cover picture:

CML Kindergarten, Lisbon, Portugal
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# Preface

### The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 29 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

### Energy in Buildings and Communities

The IEA co-ordinates research and development in a number of areas related to energy. The mission of one of those areas, the EBC-Energy in Buildings and Communities Programme, is to develop and facilitate the integration of technologies and processes for energy efficiency and conservation into healthy, low emission, and sustainable buildings and communities, through innovation and research. Until March 2013, the EBC Programme was known as the Energy in Buildings and Community Systems Programme, ECBCS.

The research and development strategies of the EBC Programme are derived from research drivers, national programmes within IEA countries, and the IEA Future Buildings Forum Think Tank Workshop, held in April 2013. The R&D strategies represent a collective input of the Executive Committee members to exploit technological opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy conservation technologies. The R&D strategies apply to residential, commercial, office buildings and community systems, and will impact the building industry in five focus areas of R&D activities:

- Integrated planning and building design
- Building energy systems
- Building envelope
- Community scale methods
- Real building energy use

### The Executive Committee

Overall control of the program is maintained by an Executive Committee, which not only monitors existing projects but also identifies new areas where collaborative effort may be beneficial. To date the following projects have been initiated by the Executive Committee on Energy in Buildings and Communities (completed projects are identified by (*)):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
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Annex 31: Energy-Related Environmental Impact of Buildings (*)
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Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: Testing and Validation of Building Energy Simulation Tools (*)
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Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
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Annex 48: Heat Pumping and Reversible Air Conditioning (*)
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Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
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Annex 53: Total Energy Use in Buildings: Analysis & Evaluation Methods (*)
Annex 54: Integration of Micro-Generation & Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance & Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy & CO2 Emissions Optimization in Building Renovation
Annex 57: Evaluation of Embodied Energy & CO2 Emissions for Building Construction
Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
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Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)
Working Group - Survey on HVAC Energy Calculation Methodologies for Non-residential Buildings
(*) – Completed

# Summary


## Introduction

Overheating in buildings is an emerging challenge at the design stage and during operation. This is due to a number of reasons including high performance standards to reduce heating demand by high insulation levels and restriction of infiltration in heating dominated climatic regions; the occurrence of higher external temperatures during the cooling season due to changing climate and urban climate not usually considered at the design stage; and changes in internal heat gains during operation are not factored in the design. Such factors have resulted in significant deviations in energy use during operation which is usually termed ‘performance gap’. In most energy performance comparative studies energy use is higher than predictions and in most post-occupancy studies overheating is a frequently reported problem. Ventilative cooling can be a solution.

## Objectives and contents of the sourcebook

The present sourcebook describes various elements necessary for the succesful implementation of ventilative cooling systems in detail and gives hands on information on their application and control strategies. Furthermore algorithms for air flow estimation as well as key performance indicators are stated.

Short summaries of national projects, ranging from the use of ventilative cooling application in schools and frozen food supermarkets to thermal comfort investigations, conducted within the course and by the participants of the Annex 62 are presented in the middle section of this document.

The sourcebook also offers an overview of software simulation tools and their ability to represent ventilative cooling in thermal calculations and concludes with the comparison calculation of a test case scenario.

## Scope and target group of the sourcebook

The introduced components and strategies address residential and non-residential buildings as well as natural, mechanical and hybrid ventilation systems. The ventilative cooling sourcebook is for architects, HVAC designers and facility managers with the goal of designing and operating energy efficient buildings making use of ventilative cooling to achieve indoor thermal comfort.

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# Abbreviations

| Abbreviations | Meaning |
|---|---|
| AC | Air-conditioning |
| AT | Austria |
| BCVTB | Building controls virtual test bed |
| BPST | Building performance simulation tool |
| BSRIA | Organization |
| CAV | Constant air volume system |
| CFD | Computational fluid dynamics |
| COP or EER | Coefficient of performance, energy efficiency ratio |
| DBT | Dry bulb temperature |
| DC | Direct current |
| DCV | Demand control ventilation system |
| DDC | Direct Digital Control |
| DEC | Direct evaporative cooling |
| DK | Denmark |
| EBC | Energy in Buildings and Communities Programme |
| EN | European Standard |
| FI | Finland |
| FSEC | Florida solar energy center |
| HEVAC or HVAC | Heating, ventilating and air conditioning |
| IAQ | Indoor air quality |
| IE | Ireland |
| IEA | International Energy Agency |
| IEC | Indirect evaporative cooling |
| ISO | International standard organization |
| JP | Japan |
| NO | Norway |
| NREL | National renewable energy laboratory |
| ORNL | Oak Ridge national laboratory |
| PCM | Phase change material |

| Abbreviations | Meaning |
|---|---|
| PDEC | Passive downdraught evaporative cooling |
| PIR | Passive infrared detector |
| PMV | Predicted mean vote |
| POF | Percentage of opening area to floor area ratio |
| PPD | Predicted percentage of dissatisfied |
| PV | Photovoltaics |
| R&D | Research and development |
| SEER | Seasonal energy efficiency ratio |
| SFP | Specific fan power |
| SOTAR | State of the art review |
| TMY3 | Weather file for TRNSYS software |
| UK | United Kingdom |
| VAV | Variable air volume system |
| VC | Ventilative cooling |
| VOC | Volatile organic compound |
| WBD | Wet bulb depression |
| WBT | Wet bulb temperature |
| ZEB or NZEB | Zero energy building (nearly) |

# Definitions

Editorial remark: The definition of terms is meant to contain explanations of technical terms with special focus on component performance criteria. If appropriate, the explanations should correspond to other pieces of IEA Annex 62 deliverables and should correspond to / point at international standards.

**Active or mechanical cooling (kWh)**

Cooling of the indoor environment by mechanical means used to provide cooling of supply air, fan coil units, cooled surfaces and others [1].

**Actuator**

Mechanical component, integrated to ventilation systems, that is responsible for moving or controlling it (i.e. linear, chain, rotary and others). It is activated automated through gateways [2].

**Adaptation**

Physiological, psychological or behavioural adjustment of building occupants to the interior thermal environment in order to avoid discomfort [1].

**Adiabatic cooling**

A process of reducing heat through a change in air pressure caused by volume expansion [2].

**Adventitious opening ($m^2$)**

An opening within the building envelope which, in terms of ventilation, is unintentional, i.e. cracks around doors and windows (airflow path or air leakage; [3]).

**Air change rate (ach)**

The volumetric rate at which air enters (or leaves) a building or zone expressed in units of building or zone volume [3].

**Air conditioning**

The artificial process of treating air to adjust its temperature, humidity, cleanliness, air quality, circulation and distribution as required by occupants, a process or a product in the space [3].

**Air curtain**

A stream of high velocity, temperature controlled air which is directed downward across an opening. It is designed to exclude exterior draughts, and pollutants blown in from outside. It also prevents the transfer of heat across the boundary, and permits the air – conditioning of a space with an open entrance [3].

**Air density ($kg/m^3$)**

Mass per unit volume of air in specific temperature and pressure [2].

**Air distribution**

The delivery of outdoor air to various spaces in a building, by mechanical means or natural forces [2, 3].

**Air flow model**

Computational model that describes the air distribution of a zone or building [2].

**Air flow rate (kg or $m^3$/time units)**

The mass or volume of air moved per unit of time through a flow opening or duct [3].

**Air inlet or outlet ($m^2$)**

A deliberate opening in a room or a duct wall for the provision of outdoor or conditioned air into the room. A deliberate opening in a building envelope or a duct through which air is expelled to the outside [3].

**Air pressure (Pa)**

The force per unit area that air exerts on any surface in contact with it [3].

**Air velocity (m/s)**

The rate relative to the surroundings and direction of air movement (air speed). Air velocity is measured with an anemometer, usually as part of a common weather station [3].

**Air vents or slot-trickle vents**

A purpose provided air inlet or outlet (airflow guiding ventilation components; [3]).

**Airing**

Intentional opening of windows, doors, vents, and others for increasing the ventilation in a room [3].

**Airtightness (ach)**

A general descriptive term for the leakage characteristics of a building. The smaller the air leakage rate at a given pressure difference across a building envelope, the greater the airtightness [3].

**Aperture effective openable area ($m^2$)**

The effective openable area of an aperture results in from the multiplication of the geometric openable area and the performance indicator of aerodynamic permeablitity, discharge coefficient ($C_d$; [2]).

**Aperture openable area ($m^2$)**

The openable area of an architectural aperture is the sum of all the open cross-section areas, which allow air to pass. Regarding ventilative cooling, the effective openable area of an aperture is direct proportional to the airflow at a given pressure difference [2].

**Aperture size ($m^2$)**

The size of a window, rooflight or door including frames and glazing area (architectural aperture). The aperture size as such is no appropriate criterion of venilative cooling performance [2].

**Atria**

An open space in the middle or at the edge of a building, usually enclosed, but still allowing the penetration of light (airflow enhancing ventilation building components; [3]).

**Attic**

A low storey or structure above the main part of a dwelling. Alternatively known as a loft or roofspace (loft or roofspace; [3]).

**Automated window opening**

Window configuration that is activated based on an integrated automation and defined control strategies. It may be part of the building management system [2].

**Balanced supply-extract ventilation system**

A ventilation system in which fans both supply and extract air from an enclosed space at equal rates [3].

**Blower door test**

A measurement technique used to evaluate the airtightness of a building or component. The air inside the room or building is extracted by the use of a fan, creating a lower pressure inside (for example 4 Pa), than outside the room or building [3].

**Box fan**

A household electric fan [2].

**Building element**

Integral component of the technical building systems or of the fabric of a building [4].

**Building envelope**

The total area of the boundary surfaces of a building through which heat light, air and moisture are transferred between the internal spaces and the outside environment [3].

**Building management system**

Building management system. A building-wide network which allows communication with and control of items of HVAC plant. May also include other systems such as lighting [5].

**Burglary prevention**

Opening system protection mechanism against unauthorized access [2].

**Buyoancy**

An upward force exerted by a fluid (i.e. air) that opposes the weight of an immersed object [2].

**Ceiling fan**

A ceiling mechanical device employing rotating aerofoil blades or vanes to continuously move air from one place to another [].

**CFD analysis**

Numerical analysis to solve and analyze problems that involve fluid flows (i.e. air; [3]).

**Climate cooling potential**

Calculation process for the evaluation of the passive cooling potential of a specific climatic condition (i.e. outdoor air temperature and wind velocity; [2]).

**Condensation**

The precipitation of liquid from its vapour phase resulting from the lowering of temperature at constant pressure: especially the deposition of water from moist, warm air onto a relatively cold surface or between two surfaces such as within a cavity wall [4].

**Conduction or conduction heat loss (kWh)**

The transfer of heat from one part of a substance to another part of the same substance and then to another substance in physical contact with it, without appreciable displacement of the molecules forming the substance [4].

**Control function**

A term used to describe type of control, i.e. compensation, night set back and other [6].

**Control parameter**

A preset variable used in a control algorithm, i.e. width of the proportional band [6].

**Controlled variable**

The physical quantity being control-led by the system, i.e. air temperature [6].

**Convection (kWh)**

Transference of heat through a liquid or gas by the actual movement of the fluid. Portions in contact with the source of heat become hotter, expand, become less dense, and rise: their place is then taken by colder portions, thus setting up convection currents [4].

**Comfort zone**

The range of indoor conditions considered acceptable by a certain proportion of the people working or living in the space [1, 43].

**Cooling (kWh)**

The transfer of energy from a body of solid liquid or gas by the existence of a temperature gradient from that body to its surroundings which are at a lower temperature, and may also be solid, liquid or gas. Heat extraction from a space for improving thermal comfort. This process is the opposite of heating [2, 3].

**Cooling season**

Part of the year during which passive or active cooling systems are needed to keep the indoor temperatures at specific levels [1].

**Cracks or crack length (m or m$^2$)**

Small gaps around doors, windows and other parts of a building envelope through which ventilation air may pass [3].

**Cross ventilation**

Air enters on one side of a room and leaves on a different side of the same room. Airflow between the entry and exit provides ventilation. Also used for flow between rooms, where the inlet is in one room and the outlet is in another [3].

**Damper**

Damper is a valve or plate that stops or regulates the flow of air inside a duct, chimney, air handler, or other air-handling equipment. Manual dampers are turned by a handle on the outside of a duct. Automatic dampers are used to regulate airflow constantly and are operated by electric or pneumatic motors, in turn controlled by a thermostat or building automation system (airflow guiding ventilation components; [2]).

**Degree days (°Cdays)**

The number of degrees of temperature difference on any one day between a given base temperature and the 24-hour mean outside air temperature for the particular location. The average number of degree days for a given period is the sum of these degree days, divided by the given period [3].

**Demand control ventilation**

A ventilation strategy where the airflow rate is governed by a chosen pollutant concentration level or occupancy. This level is measured by air quality sensors located within the room or zone. When the pollutant concentration level rises above a preset level, the sensors activate the ventilation system. As the occupants leave the room, the pollutant concentration levels are reduced and ventilation is also reduced. Common pollutants are usually occupant dependent, such as, carbon dioxide, VOC, carbon monoxide, humidity or temperature [2, 3].

**Discharge coefficient ($C_d$)**

Discharge coefficient is a dimensionless coefficient relating the mean flow rate through an opening to an area and the corresponding pressure difference across the opening. It is characterizing the aerodynamic quality of an aperture. Discharge coefficient is a basic coefficient in many aerodynamic algorithms. In case of architectural apertures, the discharge coefficient lays within the narrow band of 0.6-0.7 [2, 3].

**Discomfort hours (h)**

Hours of a period where the indoor operative temperature is higher or lower of the acceptability range of the thermal comfort models [1, 2].

**Displacement ventilation**

The displacement of internal room by incoming outdoor or conditioned air without appreciable mixing of the two masses [3].

**Draft or Draught**

Excessive air movement (i.e. cold air) in an occupied enclosure causing discomfort [3].

**Dry bulb temperature (°C)**

The temperature indicated by a dry temperature sensing element (such as the bulb of a mercury in glass thermometer) shielded from the effects of radiation [3].

**Duct**

Component of a mechanical ventilation distribution system [2].

**Evaporative cooling component**

A device that cools air through the evaporation of a fluid (i.e. water; [2]).

**Extract ventilation**

A mechanical ventilation system in which air is extracted from a space or spaces, so creating an internal negative pressure. Supply air is drawn through adventitious or intentional openings [3].

**Flow coefficient (C)**

Parameter used in conjunction with the "flow exponent" in a flow equation [3].

**Flow equation**

Equation describing the airflow rate through a building (or component) in response to the pressure difference across the building (or component; [3]).

**Flow exponent (n)**

Parameter which characterises the type of flow through a building (or component) and is used in conjunction with flow coefficient in a flow equation. When n = 1 flow is laminar, and when n = 0.5 flow is assumed turbulent. For most openings, n takes a value between these two extremes [3].

**Free running operation mode**

Naturally ventilated space without the use of HVAC systems [2].

**Gateway**

A device that connects two or more dissimilar networks by message translation and signal conditioning, permitting information exchange between them [5].

**Glazing to wall ratio (%)**

The percentage of the glazing façade in respect to the wall area for a specific orientation [2].

**Grille**

Grilles are air inlets and outlets, offering protection against weather, burglary, animals down to size of insects and partly noise. In contrast to louvres, standard grilles are not movable but offer fixed openings [2].

**Heat balance**

A statement of the heat input to, and heat loss from, an appliance, plant or structure, intended to account for all sources of heat and equivalent energy [3].

**Heat exchanger**

A device designed to transfer heat from two physically separated fluid streams. In buildings, it as generally used to transfer heat from exhaust warm air to incoming cooler outdoor air [3].

**Heat gains (kWh)**

Internal gains from the occupancy, appliances, domestic hot water and other sources. Solar heat gains are from the sun [2].

**Heat transfer**

The movement of heat energy from one body to another (gas, liquid or solid or combinations thereof) by means of radiation, convection or conduction [3].

**Heating (kWh)**

The transfer of energy to a space or to the air by the existence of a temperature gradient between the source and the space or air. This process may take different forms, i.e. conduction, convection or radiation [3].

**Humidification**

The process of transferring a mass of water to the atmospheric air [3].

**HVAC**

Systems used to provide heating, cooling and ventilation in buildings [2].

**Hybrid cooling**

Integration of minor and simple mechanical systems (e.g. pumps, heat exchangers, cooling towers and economizers) in natural cooling techniques that enhance the effectiveness of the natural cooling process [2].

**Hybrid mixed mode ventilation system**

System that combines mechanical and natural ventilation systems and functions in different modes and times of the day [2].

**Hybrid ventilation**

Ventilation, relying of both natural and mechanical ventilation in the same part of a building, but using different features of these systems at different times of the day or season of the year and are subject to control selecting the ventilation mode appropriate for the given situation [2].

**Indoor air quality**

The air quality within buildings, related to conditions around buildings and structures, and its relationship to the health and comfort of building occupants [2].

**Indoor climate**

The synthesis of day-to-day values of environmental parameters in a building i.e. temperature, humidity, air movement and air quality, and others, which affect the health and/or comfort of the occupants [3].

**Indoor environment**

Closed space delimited from the external environment or adjacent spaces by the building fabric [6].

**Indoor operative temperature (°C)**

The uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment [1].

**Infiltration (ach)**

The uncontrolled inward leakage of outdoor air through cracks, interstices, and other unintentional openings of a building, caused by the pressure effects of the wind and/or the stack effect (airtightness; [3]).

**Intentional ventilation**

Ventilation provided through the use of purpose provided openings [3].

**Internal pressure (Pa)**

The pressure inside a building envelope or space. Usually expressed with respect to outside or atmospheric pressure [3].

**Interzonal air flow**

The process of air exchange between internal zones of a building [3].

**Laminar flow**

Flow in which fluid moves smoothly. In thix flow form cross stream momentum transfer takes place by viscous action alone and mixing between flow strata does not occur [3].

**Latent cooling load (W)**

Hourly mean value of the latent heat in the water vapour to be extracted from the internal environment to maintain the intended space air moisture conditions [4].

**Leakage area ($m^2$)**

The actual open area of a hole or gap at the enveolope of a room or building [3].

**Leeward**

The opposite position of the direction of the wind [2].

**Long-term evaluation assessment**

Thermal comfort assessment over a longer period i.e. summer [2].

**Louver**

A louver is a window blind or shutter with horizontal slats that are angled to admit light and air, but to keep out rain and direct sunshine. The angle of the slats may be adjustable, usually in blinds and windows, or fixed (airflow guiding ventilation components; [2]).

**Manually operated opening**

Ventilation systems operated by the occupants [2].

**Mean radiant temperature (°C)**

The uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure [2].

**Mechanical ventilation**

Ventilation, where the air is supplied or extracted from the building or both by a fan and using supply and exhaust air terminal devices, ducts and roof/wall inlets and outlets [2].

**Mechanical ventilation strategies**

Control strategies for the use of a mechanical ventilation system [2].

**Multi-zone building**

A building or part of a building that comprises a number of zones or cells [3].

**Natural cooling (kWh)**

The use of natural heat sinks for heat dissipation from indoor spaces. Typical sinks include outdoor air (ventilative cooling), upper atmosphere/night sky (radiative cooling), earth/soil (earth coupling, ground cooling) and water (evaporative cooling; [2]).

**Natural ventilation**

Ventilation, where the air is moved by natural driving forces into the building through intentionally provided openings in the envelope and leaves the building through intentionally provided openings in the envelope, cowls or roof outlets, including vertical ducts used for extraction [2].

**Neutral pressure level**

Level at which the air pressure difference, derived from the stack effect between inside and outside a building is zero [3].

**Night cooling (kWh)**

Utilization of differences between indoor and outdoor temperatures for airborne cooling by means of ventilation at night during warm periods, with the purpose of removing accumulated heat from the building stock and thereby achieving a lower indoor temperature in the morning [2].

**Night ventilation**

Ventilation of a space, room or building during the night time. The night time cooling potential is higher compared with the day potential [2].

**Occupant behaviour**

The pattern of activity of occupants in a building, including the number of occupants, their distribution, activities and time spent within the building, and how they interact with the buildings facilities, such as ventilation systems, window opening and others [3].

**Occupied time (h/day)**

The time during which people are in a building [3].

**Optimal operative temperature (°C)**

The operative temperature that satisfies the greatest percentage of occupants at a given clothing and activity level in the current thermal environment [1].

**Outdoor air temperature (°C)**

Air taken from the external surroundings and therefore not previously circulated through the system [3].

**Overheating**

The result of the external and internal heat build up indoors (risk, severity, likelihood; [2]).

**Passive cooling (kWh)**

Covers processes and techniques to provide protection and/or prevention of external and internal heat gains in buildings as well as processes and techniques for heat modulation that allow the building to absorb and store heat for dissipation at a later stage [2].

**Passive strategies**

Control strategies for ventilation systems that consume no or minimum energy for the conditioning of a space [2].

**Pollution concentration**

The concentration within a given portion of air of harmful or unpleasant contaminants such as noxious gases or dust particles. Concentrations are often expressed as time weighted values over 24 hours, a working day or a working week [3].

**Precipitation (mm)**

Rainfall [2].

**Pressure coefficient**

A dimensionless coefficient relating the velocity pressure on the outer surface of the building to the velocity pressure derived from the mean wind velocity at a reference point [3].

**Pressure difference (Pa)**

The difference in pressure across a building envelope or component whether caused by natural or artificial means [3].

**Pressure provided opening**

An opening in the building envelope for the specific purpose of supplying or extracting ventilation air [3].

**Pressurization**

A method of testing air leakage of a building or component by installing a fan in the building envelope, for example through a door or window, and creating a static pressure excess inside the building. The airflow rate through the fan and the pressure difference across the envelope are measured from which the air leakage is assessed [3].

**Prevailing wind direction**

Main wind direction [2].

**Purge ventilation**

Also known as plug flow (piston flow), and displacement flow, and is regarded as the most efficient form of ventilation. The ventilation air acts as a piston, which pushes the "old" air in the room in front of it without actually mixing. Therefore, all of the air that reaches an arbitrary point from a small packet of fresh air at the inlet does so at the same time; this time is by definition, the local mean age of air at this point [3].

**Radiation**

The transmission of heat through space by the propagation of infrared energy; the passage of heat from one object to another without necessarily warming the space between [3].

**Recirculation air**

Extracted air which is re-supplied to a space. Recirculated air is normally blended with outside air and is reconditioned [3].

**Relative humidity (%)**

The ratio of the partial pressure of water vapor to the equilibrium vapor pressure of water at a given temperature [2].

**Running mean outdoor temperature (°C)**

Exponentially weighted running mean of the daily mean external air temperature [1].

**Sensible heat transfer**

The heat absorbed or evolved by a substance during a change of temperature that is not accompanied by a change of state [3].

**Sensor $CO_2$/Relative humidity/VOC**

Monitoring device that measures the carbon dioxide concentration, relative humidity or VOC concentration of a zone [2].

**Silencer**

Component for the decrease of the noise level, integrated in a ventilation component [2].

**Single side ventilation**

Airing with openings located on only one side of the ventilated zone [2].

**Slab radiant cooling**

Cooling process based on the low temperature of the building enevelope elements (i.e. concrete slab; [2]).

**Solar chimneys**

A vertical shaft utilizing solar energy to enhance the natural stack ventilation through a building (convection of air heated by passive solar energy; airflow enhancing ventilation building components; [2]).

**Stack effect**

The pressure differential across a building caused by the differences in the density of the air due to an indoor-outdoor temperature difference [3].

**Stratified air**

The formation of layers of different densities, in a body of fluid that is not mixed well. The variation in densities may be due to difference in temperatures (thermal stratification; [3]).

**Stroke**

The range of movement of a linear actuator [5].

**Temperature (°C)**

A property of an object which determines the direction of heat flow. When the object is placed in thermal contact with another object, heat flows from the higher temperature object to the lower temperature one [3].

**Temperature difference/gradient (°C)**

The difference between outdoor and indoor temperature [2].

**Thermal comfort**

The state of mind that expresses satisfaction with the surrounding thermal environment [2].

**Thermal mass**

A property of the mass of a building which enables it to store heat, providing "inertia" against temperature fluctuations [2].

**Thermostat**

A component which senses the temperature of a system so that the system's temperature is maintained near a desired setpoint [2].

**Transition months**

Months of the year with either cooling or heating needs [2].

**Turbulence fluctuation**

Motion of fluids in which local velocities and pressures fluctuate irregularly [3].

**Undercooling or overcooling**

The indoor temperature of the space is lower than the lower limit of the thermal comfort range, for a specific building category [2].

**Uniform mixing**

The combining of two or more substances such that the parts of one are wholly distributed throughout the parts of another [3].

**VAV system**

A ventilation system that controls the dry bulb temperature within a space by varying the volume of supply air, rather than the supply air temperature [3].

**Ventilation**

The process of supplying or removing air, by natural or mechanical means to and from a space [3].

**Ventilation air**

That portion of supply air that is outdoor air plus any recirculated air that has been treated for the purpose of maintaining acceptable indoor air quality [3].

**Ventilation effectiveness**

An expression describing the ability of a mechanical (or natural) ventilation system to remove pollution originating in a space, either of a steady state or transient nature [3].

**Ventilation efficiency**

A series of indices which indicate the mixing characteristics of incoming outdoor air with the air already present in an enclosure and which characterise the pollutant distribution within that enclosure resulting from the interaction of air flow with internal pollutant sources [3].

**Ventilation heat loss/gains**

The heat lost or gained by virtue of warm and/or humid air flowing into or leaking from a space [3].

**Ventilation rate (ach)**

The rate at which outside air is intentionally supplied to a building or zone. Sometimes ventilation is used to describe the total mechanical air change in a room or building. This rate may then frequently comprise a considerable proportion of recirculated rather than outdoor air. Hence when apparently very large ventilation rates are quoted, it is important to establish the proportion of flow representing outside supply air. The remainder will be recirculated air [3].

**Ventilation strategy**

A plan by which ventilation air is purposefully provided to a space. When such a strategy is employed, it is normal to take action to minimise background leakage [3].

**Ventilation system**

A combination of appliances or building components designed to supply indoor spaces with outdoor air and/or to extract polluted indoor air [1].

**Ventilative cooling**

Utilization of differences between indoor and outdoor temperatures for airborne cooling by means of ventilation to reduce or even eliminate the cooling loads and/or the energy use by mechanical cooling in buildings, while resulting in a comfortable thermal environment [2].

**Venturi ventilator**

The Venturi effect is the phenomenon that occurs when a fluid flowing through a pipe or similar is forced through a narrow section, resulting in a pressure decrease and a velocity increase. Powerless rotating ventilators are making use of wind speed for creating negative pressure and enhancing exhaust air flow (airflow enhancing ventilation building components; [2]).

**Wind catcher or scoop**

Wind catchers utilize the wind speed in elevated levels above ground, by special construction of the hood forcing the wind down into the chimney. There are mono-directional and bi-directional windcatchers, the latter ones introducing downward air driven by wind pressure at the windward side of the windcatcher (airflow enhancing ventilation building components). High massive constructions are named wind towers [2].

**Wind pressure (Pa)**

The difference between the local pressure on the exterior of a building induced by the action of the wind and static outdoor pressure far away from any building or shield [3].

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# 1. Introduction

## 1.1. General context

Extrapolating current trends in energy supply and use suggests that existing goals to mitigate carbon emissions and to reduce non-renewable energy consumption will not be met. To change the looming path it is crucial to identify existing large and promising reduction potentials.

## 1.2. Main Goals of IEA-EBC Annex 62 Ventilative Cooling

The main goal is to make ventilative cooling an attractive and energy efficient cooling solution to avoid overheating of both new and renovated buildings. Ventilation is already present in buildings through mechanical and/or natural systems and it can remove excess heat gains as well as increase air velocities and thereby also widen the thermal comfort range.

## 1.3. Main targets

The results from the Annex will facilitate better possibilities for prediction and estimation of heat removal and overheating risk – for both design purposes and for energy performance calculation. The documented performance of ventilative cooling systems through analysis of case studies will promote the use of this technology in future high performance and conventional buildings.

To fulfil the main goal of the Annex the following are the targets for the research and development work:

- To develop and evaluate suitable design methods and tools for prediction of cooling need, ventilative cooling performance and risk of overheating in buildings.
- To develop guidelines for an energy-efficient reduction of the risk of overheating by ventilative cooling solutions and for design and operation of ventilative cooling in both residential and commercial buildings.
- To develop guidelines for integration of ventilative cooling in energy performance calculation methods and regulations including specification and verification of key performance indicators.
- To develop instructions for improvement of the ventilative cooling capacity of existing systems and for development of new ventilative cooling solutions including their control strategies.
- To demonstrate the performance of ventilative cooling solutions through analysis and evaluation of well-documented case studies.

# 2. Foreword

This sourcebook is one of the final deliverables of IEA EBC Annex 62, which are as follows:

1. State of the art review, published in 2015
2. Ventilative cooling application database, published in 2016
3. Ventilative cooling potential tool, published in 2017
4. Guidelines for ventilative cooling design and operation, published in 2018
5. Ventilative cooling sourcebook, published in 2018
6. Ventilative cooling case studies, published in 2018
7. Recommendations for legislation and standards, published in 2018

The sourcebook presents new developed ventilative cooling components, through the national research projects and describes them on a typological level, gives design and product examples, highlights characteristic performance indicators and, if appropriate, provides suggestions for best use. At the end an analytical glossary is presented in detail. The sourcebook is supplementary material for the State-of-the-Art Review (SOTAR) and it is suggested that it be used as a continuation of it.

The sourcebook is oriented to architects and building service designers, aiming to support them in selecting the right components, in appropriate quality, for implementation in their specific ventilative cooling projects.

The sourcebook structure follows the categorization of the components in the SOTAR book, which is:

- Airflow guiding ventilation components
- Airflow enhancing ventilation components
- Passive cooling ventilation components
- Automation components

A list of authors and contributors can be found in the following table, as well as a list of involved research institutes, universities and companies. On behalf of the participants we hereby want to acknowledge the members of the Executive Committee of IEA Energy in Buildings and Communities Programme (EBC) Implementing Agreement as well as the funding bodies.

The final report was co-authored by the participants listed below, and edited by the Subtask B IEA Annex 62 co-leaders Peter Holzer and Theofanis Psomas. Also thanks to the two reviewers of the sourcebook: Paul O' Sullivan, Cork Institute of Technology and Giacomo Chiesa, Politecnico di Torino.

Research participants collaboratively worked together under the umbrella of the IEA EBC framework. Duplications of work were avoided and participants benefitted from collaboration and synergies which became possible due to the strong organizational Annex 62 framework.

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# 3. Airflow guiding ventilation components

Airflow guiding components are mandatory elements in each ventilative cooling application project.

- Classical façade elements are windows, doors and rooflights (chapter 1.1);
- Specialized façade elements are flaps, grilles, louvres and dampers, offering extended possibilities of control and protection (chapter 1.2);
- Terminals are used for the special purpose of releasing air from ductwork to rooms, (chapter 1.3).

Most of the components presented in this chapter are not restricted to ventilative cooling applications. If applied in ventilative cooling applications though, they have to be selected and applied with the utmost care, taking into account substantial success criteria such as pressure drop, sensitivity towards wind-pressure, sound attenuation, rain protection, burglary protection, possibility of automation and others. The specific performance range of components regarding these criteria is presented in this chapter.

## 3.1. Windows-doors-rooflights

### *3.1.1. General aspects*

Windows, rooflights and doors are the most widespread airflow guiding components in ventilative cooling applications.

Their use has a significantly cost-advantage, since the ventilative cooling performance may be gained from a building component which is already in place for the purpose of daylight supply, view or connection to the exterior space. In addition, architectural apertures (also control) are familiar to occupants, are visible and therefore have a good chance of being maintained properly.

Furthermore, windows, rooflights and doors are generally most effective in providing high ventilation and cooling effectivity at very low pressure drop. At a given driving force of 1 Pa, with an openable geometric cross-sectional area of 1 m², operating in cross flow ventilation, a window may provide an airflow close to 3000 m³/h.

If applied to ventilative cooling, special attention has to be paid to position, size and aperture mechanism (opening angle). Architectural aperture characteristics like surrounding head, sill and jamb are also important.

Manually handled, windows, rooflights and doors may be easily transformed to automated ones with the installation of mechanical actuators. There is a broad variety of actuators available. They are presented in chapter 6.1. Blind and shading systems control is crucial for the effective design for ventilative cooling in architectural appertures.

Furthermore, windows, doors and rooflights offer good prerequisites to close tight, with effective seals, and they are robust against higher closing forces. Challenges to sealing may occur together with special window types, such as pivot hung windows or sliding windows, the latter also addressed as sash windows.

For the purpose of readability the group of 'windows, doors and rooflights' elements hereafter is addressed in short as 'architectural apertures'.

### 3.1.2. Typology

There is an immense variety of specific types of architectural apertures influenced by function, aesthetics, tradition, materials, cost and many other reasons. Hence, this chapter presents only a focused selection under the aspect of ventilative cooling, structured according to the opening mechanism.

**Bottom hung window:** Bottom hung windows are frequently used for ventilative cooling (transom windows) if adjacent to the outdoor spaces. They offer very good controllability and considerable rain protection, safety and security against burglary. Bottom hung windows offer effective cross flow and stack effect ventilation. The airflow is highly adjustable. The draft risk is low because of the direction of the flow. The low window opening percentage of the bottom hung transom windows limit the achievable airflow significantly. Furthermore, if placed near the room's ceiling, the geometric openable cross-sectional area of bottom hung transom windows may be compromised by the narrow gap between window frame and the room's ceiling.

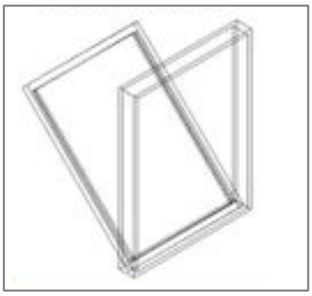


Figure 1 Bottom hung window.[1]

**Top hung window:** Top hung windows are frequently used in ventilative cooling projects, again realized as transom windows. They are usually realized in a wide but low opening percentage, but also offers very good controllability and reasonable rain protection, safety and security. Top hung windows work perfectly together with cross flow and stack effect ventilation and offer good adjustability and low draft risk.

1 http://www3.turbocadcommunity.com (30/10/2017)

Figure 2 Top hung window.[1]

**Side hung window:** Side hung windows are generally the most frequently used windows. They provide high ventilation efficiency if they are tall shaped, leading to the highest possible air exchange in the case of single sided ventilation. They have also good operability as well. Shortcomings are their low level of rain, safety and security protection. Furthermore, if automated, the airflow through side hung windows is difficult to adjust, offering significant draft risk in occupied rooms.

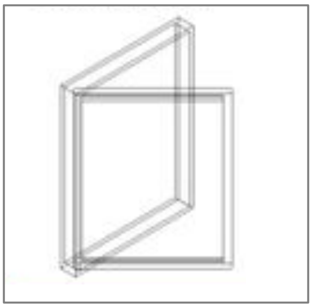


Figure 3 Side hung window.[1]

**Pivot hung window:** Pivot hung windows turn around an axis, which is mounted in the middle of the aperture. The axis may be vertical or horizontal. Pivot hung windows offer good performance in terms of ventilative cooling compared to the previous types. Shortcomings are their poor airtightness, especially around the axis.

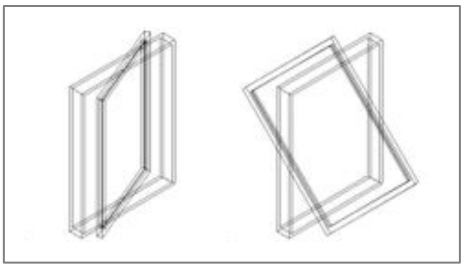


Figure 4 Vertical and horizontal pivot hung windows.[1]

**Sliding window:** Sliding windows, also referred to as sash windows, and doors, offer excellent air exchange and excellent protection against outdoor conditions. Again, shortcomings are the poor airtightness and restricted possibilities for automation integration.

Figure 5 Sliding window.[1]

### 3.1.3. Airflow through architectural apertures

Airflow magnitude through an architectural aperture is a function of the openable geometric cross-sectional area, the aerodynamic property of the aperture and the pressure drop on it (caused by temperature dfferences, wind magnitude and orientation). Scientific literature offers numerous algorithms to calculate the airflow efficiency provided through an architectural aperture. Specialized software such as airflow network modelling and airflow network modelling combined with building energy modelling include different alogorithms internally.

A robust algorithm for single sided ventilation (one opening) is that proposed by de Gids & Pfaff including airflow driving forces of temperature (buoyancy) and wind [1]:

$$U_m = \sqrt{C_1 U_{10}^2 + C_2 h \Delta T + C_3} \tag{1}$$

$$Q = \frac{1}{2} A U_m \tag{2}$$

| | |
|---|---|
| $A$ | Opening area [m$^2$] |
| $C_1$ | Wind constant (0.001) |
| $C_2$ | Buoyancy constant (0.0035) |
| $C_3$ | Turbulence constant (0.01) |
| $h$ | Window height [m] |
| $Q$ | Volume flow rate [m$^3$/s] |
| $U_{10}$ | Reference wind speed measured at the height of 10 m [m/s] |
| $U_m$ | Mean velocity [m/s] |

For different approach of single sided ventilation, driven by temperature diffence only, airflow through an architectural aperture (openings at one level only) may be estimated using the algorithm from EN 13791:2004 standard [2]:

$$m_T = C_d \rho \frac{A}{3} \left(\frac{\Delta\theta g H}{T_m}\right)^{0,5} \tag{3}$$

$C_d$ Discharge coefficient of aperture

$g$ Acceleration due to gravity (9.81m/s²)

$H$ Heigth of the opening [m]

$m_T$ Mass flow rate due to temperature difference (or volumetric airflow from aperture [m3/s])

$T_m$ Reference temperature (300 K)

$\Delta\theta$ Temperature difference between internal and external environements [°C]

$\rho$ Air density [kg/m³]

EN 16798-7:2017 standard suggests the equations below (single sided ventilation), which combines both stack and wind effects [3]. The air flow rate entering the ventilation zone through window openings is:

$$q_{V;arg;in} = 3600\ \frac{\rho_{a;ref}}{\rho_{a;e}} \frac{A_{w;tot}}{2} \cdot max\left(C_{wnd} u_{10;site}^2\ ; C_{st} h_{w;st} abs(T_z - T_e)\right)^{0,5} \tag{4}$$

$$A_{w,i} = R_{w;arg,i} A_{w;max,i} \tag{5}$$

$$A_{w;tot} = \sum_{i=1}^{N_w} A_{w;max,i} \tag{6}$$

$C_{st}$ Coefficient taking into account stack effect in airing calculations (0.0035 (m/s)/(m·K))

$C_{wnd}$ Coefficient taking into account wind speed in airing calculations (0.001 1/(m/s))

$h_{w;stm}$ Useful height for stack effect for airing [m]

$R_{w;arg,i}$ Ratio of window opening area to maximum window opening area for a window “i”

$T_e$ External temperature [K]

$T_z$ Temperature of ventilated zone [K]

$\rho_{a;e}$ External air density [kg/m³]

$\rho_{a;ref}$ Air density at sea level, 293 K and dry air (1.204 kg/m³)

$u_{10;site}$ Wind velocity on site

With a given pressure drop the airflow through an architectural aperture can be calculated with the analytical algorithm based upon mass and spin balance [4]:

$$\dot{V} = C_d \sqrt{\frac{2}{\rho}}\,\sqrt{\Delta p} A = C_F \sqrt{\Delta p} \tag{7}$$

$$(C_d)^2 = \frac{1}{k} \tag{8}$$

| | |
|---|---|
| $A$ | Opening area [m²] |
| $C_d$ | Discharge coefficient of aperture ($C_d$ for windows = 0.6-0.7; 0.67 (EN 16798-7:2017)) |
| $C_F$ | Flow coefficient of the aperture [$m^3/sPa^{0.5}$] |
| $k$ | Flow resistance (k typical for windows = 2.1) |
| $\dot{V}$ | Volumetric airflow from aperture [$m^3/s$] |
| $\Delta p$ | Pressure difference across the perimeter [Pa] |
| $\rho$ | Air density (1.21 kg/$m^3$ at 20°C and standard pressure) |

## 3.2. Dampers-flaps-louvres-grilles

### *3.2.1. General aspects*

Louvre components are an alternative to windows for ventilation inlets and exhausts. They can generally be classified as airflow guiding components. They are normally manufactured with a slotted configuration of alternating air passages and angled louvres or fins. Often, they are referred to as grilles in the literature. An example of a fixed architectural louvre is given in Figure 6.

Figure 6 Example of louvre ventilative cooling system.[2]

Louvres are an attractive alternative to windows in that they address some of the barriers to ventilative cooling that windows do not. They allow ventilation to take place while removing the risk of burglary when operated during unoccupied hours such as night cooling. They can reduce or eliminate rain ingress extending the possible operative hours of ventilative cooling. This is particularly important where ventilative cooling is required outside the traditional cooling season of May to September. As louvres are dedicated ventilation airflow paths they can result in a reduction in glazed area where the size of the window was motivated by airflow rates and this can have benefits for controlling solar

[2] http://www.duco.eu (30/10/2017)

gains. There are generally two approaches to the selection of louvre components for ventilation. Firstly, these can often be custom-made, designed specifically for the project based on architectural requirements. More commonly, they are selected from existing product lists of manufacturers.

A key consideration when selecting louvres is the area that is available for estimating airflow rates. Louvres generally have a net geometric free area somewhere in the range 40 to 60% of the overall opening area, i.e. based on the overall louvre width and height. It is important to include the appropriate value when sizing components. Most manufacturers will provide details on the likely installed airflow performance, usually in the form of the discharge coefficient ($C_d$). The manufacturer quoted coefficient of discharge for louvre components is generally below 0.61 although where possible this should be verified as part of the project design. Some caution should be exercised here. Depending on the ventilation strategy, it is important to establish whether the $C_d$ is based on buoyancy driven airflow or whether the effects of wind driven airflow have also been factored. Research has shown that for small openings the wind driven $C_d$ value in cross flow ventilation can often be larger than 0.6, particularly for small openings. However, it is difficult to obtain data about this from most manufacturers given the dependency of performance on localised installation effects. Choosing a conservative $C_d$ value will result in reliable performance. However, this can also underestimate the cooling potential of the ventilative cooling component and influence design decisions.

Often solutions will be tailored to suit the specific requirements for the ventilative cooling application. These can rely on a combination of manufacturer louvres and curtain walling support systems or can be developed as complete custom-made components for the project. Figure 7 highlights examples of more integrated custom-made solutions.

Figure 7 Examples of custom-made or project specific louvre solution.[3]

### 3.2.2. *Qualities and specifications*

Most manufacturers will quote airflow rates for their components for a 1 Pa or 2 Pa pressure difference across the opening. Table 1 gives typical ranges of louvre component dimensioning. This is based on a number of manufacturers and is intended as a guideline only for early stage design.

Table 1 Typical ranges of performance values for louvre systems.

| Parameter | Typical values |
|---|---|
| Typical air flow (0.5 $m^2$ aperture at 2 Pa; cross flow ventilation) | 263-1380 $m^3/h$ |
| Discharge coefficient range, $C_d$ | 0.2-0.7* |
| Net geometric free area ratio | 40-60% |
| Recommended design ΔP | 1-3 Pa |

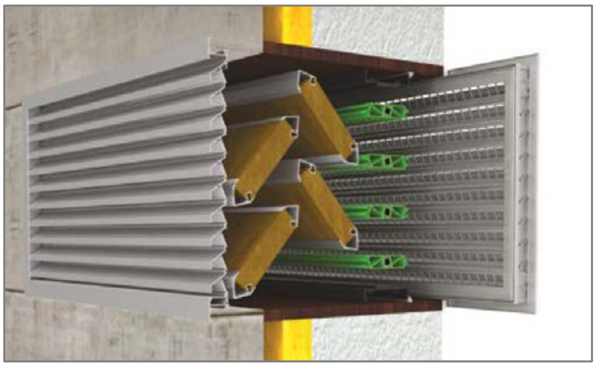
*Higher values depend on the internal airflow control solution (i.e. insulated door vs multi leaf damper).

Louvres should comply with the requirements of prEN 1627:1999 for burglary proof construction products. Water repellency and ingress should be verified according to EN 13030:2001 and ideally based on HEVAC and BSRIA testing guidelines and procedures.

Louvre systems must also incorporate some means of closing the opening when airflow is not required. This is achieved using an integrated multi-leaf motorised damper, an internal manually

[3] www.zero2020energy.com (30/10/2017)

adjustable multi-leaf damper or an internal insulated door. Examples of these are shown in Figure 8. These can include acoustic attenuation or heating components depending on the application and project design requirements. Integrated multi-leaf dampers are generally automated and work well in situations where the airflow opening is not easily accessible. These are integrated units supplied as a complete packaged unit by manufacturers.



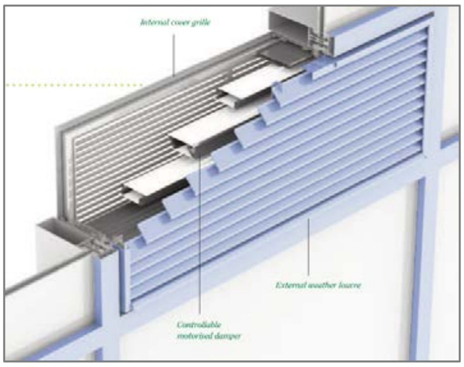



Figure 8 Examples of multi leaf damper solutions designed to control airflow through louvre systems.[3,4]

Manufacturers may not offer the multi-leaf damper or insulated door as part of their product solution, meaning a bespoke architectural design may be needed. In this instance there may not be data available on the performance of the opening so the airflow through the system should be tested or modelled to verify performance during the design stage of the project. Insulated doors can be operated as manual or automated openings and will open into the internal space. They can be bottom hung or side hung. Bottom hung are generally recommended for ventilative cooling strategies that make use of the thermal mass of an exposed concrete ceiling, directing the airflow upwards. With an aperture size of 0.5 $m^2$, values up to 300 $m^3/h$ are achievable with single sided ventilation. Substantially higher values are achievable when using cross flow ventilation. Table 2 includes equations that can be used to estimate the airflow performance of louvre systems during early stage design where no specific components have been selected.

Table 2 Empirical equations for predicting pressure driven airflow through louvre and mesh screen combinations ($f_a$ is the mesh screen free area, $\theta$ represents the louvre inclination angle and L represents the space between the louvre and mesh).

[4] http://www.passivent.com/ (30/10/2017)

Table 2 Empirical equations for predicting pressure driven airflow through louvre and mesh screen combinations ($f_a$ is the mesh screen free area, $\theta$ represents the louvre inclination angle and L represents the space between the louvre and mesh).

| Case description | Proposed equation | Range of application |
|---|---|---|
| Ventilator with horizontal blades incorporating mesh-screen (described above) | $Q = \frac{\Delta P^{0.67} 1.363^{f_a}}{12.305}$ | $0.35 \leqslant f_a \leqslant 0.7$ |
| Ventilator with louver blades inclined at an angle to the horizontal | $Q = \frac{\Delta P^{0.57} 10.591^{\cos\theta}}{82.269}$ | $0^\circ \leqslant \theta \leqslant 60^\circ$ |
| Round-wire woven-square mesh-screen lattice | $Q = \frac{\Delta P^{0.81} 83.096^{f_a}}{34.124}$ | $0.35 \leqslant f_a \leqslant 0.7$ |
| Ventilator with inclined louver blades and a mesh-screen | $Q = \frac{\Delta P^{0.63} 8.585^{\cos\theta} 1.197^{f_a}}{91.8356}$ | $0^\circ \leqslant \theta \leqslant 60^\circ$, $0.35 \leqslant f_a \leqslant 0.7$ |
| Ventilator with horizontal louver blades with gap between blades and mesh-screen | $Q = \frac{\Delta P^{0.75} 10.176^{f_a} 1.0202^{L}}{29.923}$ | $0.35 \leqslant f_a \leqslant 0.7$, $3\,\text{mm} \leqslant L \leqslant 15\,\text{mm}$ |
| Ventilator with inclined louver blades with gap between blades and mesh-screen | $Q = \frac{\Delta P^{0.71} 14.296^{\cos\theta} 4.349^{f_a} 1.0202^{L}}{265.072}$ | $0^\circ \leqslant \theta \leqslant 60^\circ$, $0.35 \leqslant f_a \leqslant 0.7$, $3\,\text{mm} \leqslant L \leqslant 15\,\text{mm}$ |

It is also possible to provide ventilation using insulated dampers or flaps without the inclusion of louvre systems. These can guide the airflow into the internal space depending on the design concept, directing flow upwards towards heavy thermal mass ceilings or downwards, to promote buoyancy or stack driven flow. These will have performance values closer to inward opening windows from chapter 1. The disadvantage of these is the increased risk to burglary and rain ingress. However, they can produce larger airflow rates when compared with louvre solutions. An example of flap dampers is given in Figure 9. To avoid draft risk flap dampers are best positioned in the outside wall, close to the ceiling opening upwards to direct the air towards the ceiling. They may be placed close to the ceiling to take advantage of the coanda effect.

Figure 9 Examples of ventilation flaps.[5]

## 3.3. Terminals

Terminals are generally understood as technical openings which guide inlet air into the ventilated space or guide them out from the room. They may be connected to either a ductwork or directly to the outside air. Apart from windows, which are acting as inlet or outlet openings or both at once, terminals are generally used as one-way ventilation elements. Ahead of simple window opening, terminals are frequently equipped with some kind of damper to control the flow rate and/or to attennuate noise transfer. There is a broad variety of terminals offered for different kinds of ventilation purposes. They vary in their design airflow, pressure drop, sound attenuation, controllability, design, airflow distribution pattern and others. Hereafter a focused selection under the aspect of ventilative cooling is presented.

### *3.3.1. Window ventilators, trickle vents, slot or discular diffusers, disc valves*

Window ventilators, often addressed as trickle vents or slots, usually placed adjacent to the window frame or even integrated into the frame (Figure 10). They serve as inlet vents for direct outside air, frequently in combination with exhaust ventilation. Most trickle vents are manually operable from the

[5] http://www.gaugele.com (30/10/2017)

inside, which allows opening and closing them with some kind of in-between position. Trickle vents are also available with sound attenuation functionality, with wind pressure dependent pressure drop, with integrated sound damper and insect mesh. There are trickle vents with a supporting ventilator available. The general advantage of trickle vents is their smart integration into the window, with avoiding additional damage of the insulation layer or of the vapour barrier. Furthermore, it might be of advantage, having the position of the controlled air inlet at the very same position of the natural ventilation unit (i.e. window).

A shortcoming of trickle vents regarding ventilative cooling may be their limitation of the airflow provided. Still, optimized trickle vents offer air flows in the range from 25 to even 50 m³/h per meter of slot vent at a pressure difference of only 1 Pa, which is very much suitable for both hygienic ventilation and ventilative cooling.

Besides, trickle vents placed on top of the window may cause draft risk, when cold air enters downwards and even is accelerated by the cool window pane. To prevent this, specialized trickle vents guide the airflow towards the ceiling.

Figure 10 Window with trickle ventilation.[6]

Slot diffusers work similarly to trickle vents and window ventilators. Since they are not integrated into the frame they are not so limited in size and therefore offer higher airflows at low pressure drop.

Disc valves and circular diffusers are frequently applied in mechanical hygienic ventilation (Figure 11). They cover a wide range of air flows, from 30 m³/h up to > 1.000 m³/h per unit. They usually allow precise airflow control. Circular diffusers are typically built for high rates of air mixing and thus reducing draft risks. As a result, they need noticeable levels of pressure drops, ranging from 10 to 40 Pa or even higher, limiting their applicability in naturally driven ventilative cooling projects.

[6] http://export.renson.eu (30/10/2017)

Figure 11 Disc valve.[7]

### 3.3.2. Qualities and specifications

***Airflow through terminals***

Airflow through terminals is calculated from the aerodynamic properties of the terminal and the pressure difference. Apart from architectural openings, the aerodynamic qualities of terminals are usually subsumed by the flow coefficient ($C_F$), leading to the volumetric airflow.

$$C_F = C_d A \sqrt{\frac{2}{\rho}} \tag{9}$$

$$\dot{V} = C_F \sqrt{\Delta p} \tag{10}$$

| | |
|---|---|
| $A$ | Opening area [m²] |
| $C_d$ | Discharge coefficient of terminal |
| $C_F$ | Flow coefficient of the terminal [$m^3/sPa^{0.5}$] |
| $\dot{V}$ | Volumetric airflow from terminal [$m^3/s$] |
| $\Delta p$ | Pressure difference across the perimeter [Pa] |
| $\rho$ | Air density (1.21 kg/$m^3$ at 20°C and standard pressure) |

Even more often, manufacturers offer tables or diagrams of performance, indicating the terminal's airflow at given pressure differences.

***Airflow regulation***

Terminals may be manually or automatically controlled. In case of manual regulation, a control range of the airflow in the range of 30% to 100% of the design air-flow may be expected, additional to full closing. Regulation to a proportion of less than 30% of the design airflow might lead to noise

[7] http://www.saiductfab.co.in/disc-valve.html (30/10/2017)

problems. In case of automation, regulations are depending on the wind pressure and relative humidity.

***Sound attenuation***

In case of night ventilation sound attenuation of terminals is an important issue. Sound attenuation should preferably follow the principle of a splitter silencer, causing the least possible pressure drop. Solutions with the air passing through a permeable, sound insulating material are not favourable in ventilative cooling applications, due to their high pressure drop. Sound reduction indices of terminals in the range of 25 up to 50 dB in open position may be achieved.

***Burglary protection***

Antiburglary protection of terminals is defined in prEN 1627:1999 (class 2 similar to window class WK2).

## 3.4. References


1) De Gibs W, Phaff H. Ventilation rates and energy consumption due to open windows: A brief overview of research in the Netherlands. Air Infiltration Rev. 1982;4:4-5.
2) European Committee for Standardization. EN 13791: 2004. Thermal performance of buildings - Calculation of internal temperatures of a room in summer without mechanical cooling - General criteria and validation procedures (ISO 13791:2004). Brussels: ECS; 2004.
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4) Etheridge D, Sandberg M. Building ventilation-Theory and measurement. UK: John Wiley & Sons Ltd.; 1996.

# 4. Airflow enhancing ventilation components

In this chapter, airflow enhancing components are presented:

- Powerless ventilators are presented in chapter 4.1;
- Chimneys are presented in chapter 4.2;
- Mechanical ventilators are presented in chapter 4.3.

Airflow enhancing components are not restricted to ventilative cooling applications. If applied in ventilative cooling applications though, they have to be selected and applied knowing the air volume flows that may result (typically high).

## 4.1. Powerless ventilators

Powerless ventilators generally make use of wind pressure to generate either additional pressure driving supply air flow or - more often - generate a negative pressure driving extract air. The most widely used are venturi ventilators, powerless rotating ventilators and wind scoops.

Powerless ventilators are generally robust, cheap and very effective. Again, their effects depend inevitably on the presence of wind.

### *4.1.1. Venturi ventilators*

The venturi effect is the phenomenon of pressure decrease within a fluid passing a narrow section of ductwork. Physical basis of the the effect is the Bernoulli equation (at any arbitrary point along a streamline):

$$\frac{u^2}{2} + \frac{p}{\rho} + gz = constant \quad (11)$$

*g* Acceleration due to gravity (9.81m/s²)

*p* Operating pressure [Pa]

*u* Velocity of incompressible fluid [m/s]

*z* Geodetic altitude [m]

*ρ* Air density [kg/m³]

The venturi effect may be utilized for providing a negative pressure at extract vents and thus enhancing ventilation. Venturi elements for ventilative cooling may be shaped as venturi roofs or venturi roof ventilators. The driving ventilation force can be significant, depending on the square of the air velocity.

$$p_{wind} = C_p \, {}^{\rho}\!/_{2} \, v^2 \qquad (12)$$

$C_p$ Pressure coefficient (negative value)

$p_{wind}$ Wind pressure, additive to static pressure of the free stream [Pa]

$v$ Flow speed of the free stream [m/s]

$\rho$ Air density at sea level (1.204 kg/m³)

Industrial venturi ventilators reach pressure coefficients up to (– 1), leading to remarkable negative pressures of:

- 4 Pa at an undisturbed wind speed of 2.5 m/s;
- up to 60 Pa at an undisturbed wind speed of 10 m/s.

Venturi roofs ventilators and venturi chimney caps are offered throughout the world as robust and effective air flow enhancing devices for exhaust air (Figure 12).

Figure 12 Prefab airstract ventilator utilizing venturi effect.[8]

Another venturi ventilator is the wind jetter presented in Figure 13. It uses wing theory to accelerate air on the underside of the system thus causing a negative pressure, which exhausts air, much like an inverted aircraft wing. The large rudder ensures that the jetter is always facing the wind in the appropriate direction.

[8] http://www.passivent.com/downloads/airstract_vents.pdf (30/10/2017)

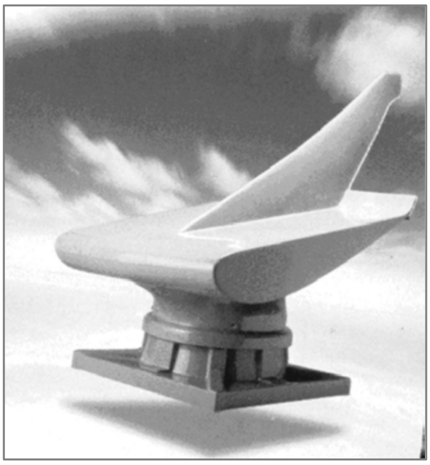

Figure 13 Wing jetter system.[9]

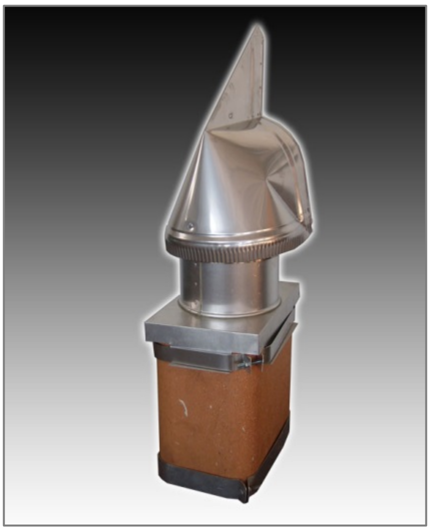

Figure 14 Exhaust windscoop.[10]

### *4.1.2. Powerless rotating ventilators, windcatchers and supply air windscoops*

Powerless rotating ventilators, also addressed as wind ventilators, are mounted on the roofs. They use also the external wind pressure, providing negative pressure to extract ducts and vents. They are generally robust, relieable and rainproof. Powerless rotating ventilators are offered at pipe diameters up to 900 mm (Figure 15).

Wind ventilators offer significantly high exhaust capacities:

[9] HASEC corporation, Japan
[10] www.scoopsandrakes.com (30/10/2017)

- At wind speeds of > 1.5 m/s ranging from 800 $m^3/h$ (300 mm diameter) up to 5.000 $m^3/h$ (900 mm diameter);
- At wind speeds of > 3.0 m/s ranging from 1500 $m^3/h$ (300 mm diameter) up to 9.000 $m^3/h$ (900 mm diameter).

Shortcomings are the thermal bridges and the condensation risk, if applied in cold climates. Accessories are available, such as fire protectors or dampers (manual or electrical; powerless temperature driven).

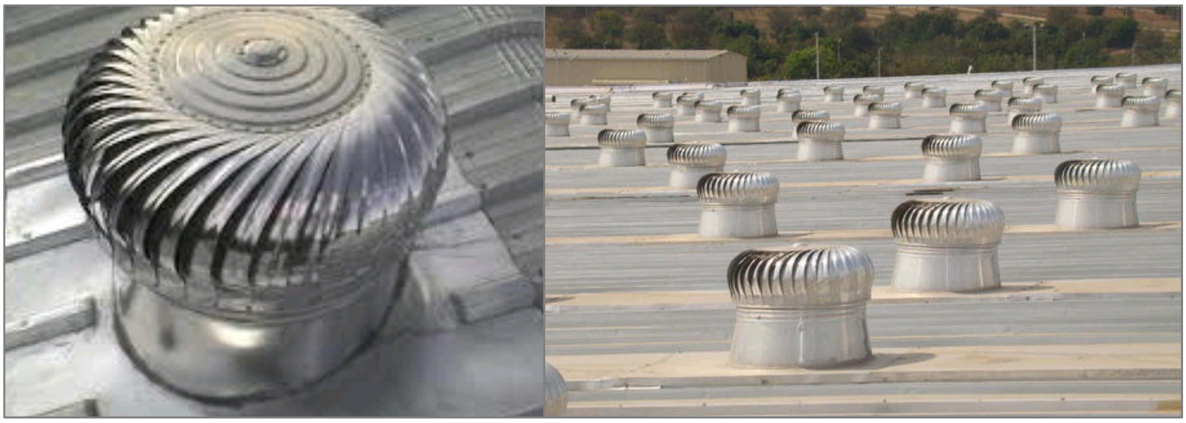

Figure 15 Powerless roof ventilators.[11]

**Windcatchers and supply air windscoops**

In contrast to venturi ventilators and powerless rotating ventilators, windcatchers and supply air windscoops are designed as supply air ventilators. Amongst windcatchers there are also hybrid constructions.

Windcatchers are traditional elements of vernacular Middle Eastern architecture, particularly in the Persian Gulf region, i.e. Iran, Iraq, Dubai, Qatar, and others countries and North African regions, i.e. Algeria, Egypt (dry climates) and others. Over the past three thousand years they have been the major cooling technology of buildings in those regions.

Windcatchers utilize the wind speed in elevated levels above ground, by special construction of the hood forcing the wind down into the chimney. In several cases, the effect is enforced by evaporative elements within the windcatcher. Traditionally the cooling effect from windcatchers is used to support local zones/places within the building or within the building's courtyard.

There are mono-directional and bi-directional windcatchers (Figure 16) The latter ones driving air downward by wind pressure at the windward side of the windcatcher and introducing an upward air flow by wind suction at the leeward side of the windcatcher. Both airflows may be assisted by buoyancy: In case of the inlet air evaporative cooling may be introduced, increasing the inlet air-flow.

[11] http://www.industrialairventilator.com/ (30/10/2017)

Buoyancy may assist the extract air flow when indoor temperature exceeds outdoor temperature. Air evaporative cooling may be introduced to the construction, increasing the inlet air-flow.

There is a significant amount of scientific literature available studying the function of vernacular and modern windcatchers [1], [2]. There are also recent developments of modern, prefabricated windcatchers, some of them replacing the traditional form of the wind tower by the new form of windscoops, with only mono-directional function for either supply or extract air. Still, windcatchers are very much tailor made and have to be, since their function is intrinsically linked to the local building site, the prevailing wind conditions in space and time, and last but not least, to the building itself.

Windcatchers depend on the sensitive balance of the air flow driving forces, which are wind and temperature differences, and the air flow network within the building, including components of heat storage and evaporative cooling.

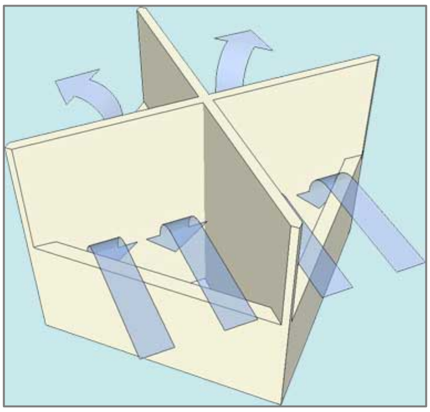

Figure 16 Bidirectional windcatcher functional principle.[12]

Figure 17 Schematic drawing of a supply air windscoop.[13]

[12] http://catnaps.org/islamic/gulfarch4.html (30/10/2017)

[13] http://www.canadianarchitect.com/asf/principles_of_enclosure/environmental_mediation/environmental_mediation.htm (30/10/2017)

Figure 18 shows an example of a modern bidirectional windcatcher with PV-driven assisting fan. The bidirectional windcatcher 'Solaboost' is divided into four sections, working bidirectional at all wind directions. A 10 W monocrystalline photovoltaic solar module is integrated, linked to an assisting fan (2 W at nominal power), adding up to 35 l/s in addition to 110 l/s ventilation calculated at between 2 and 3 m/s external wind speed.

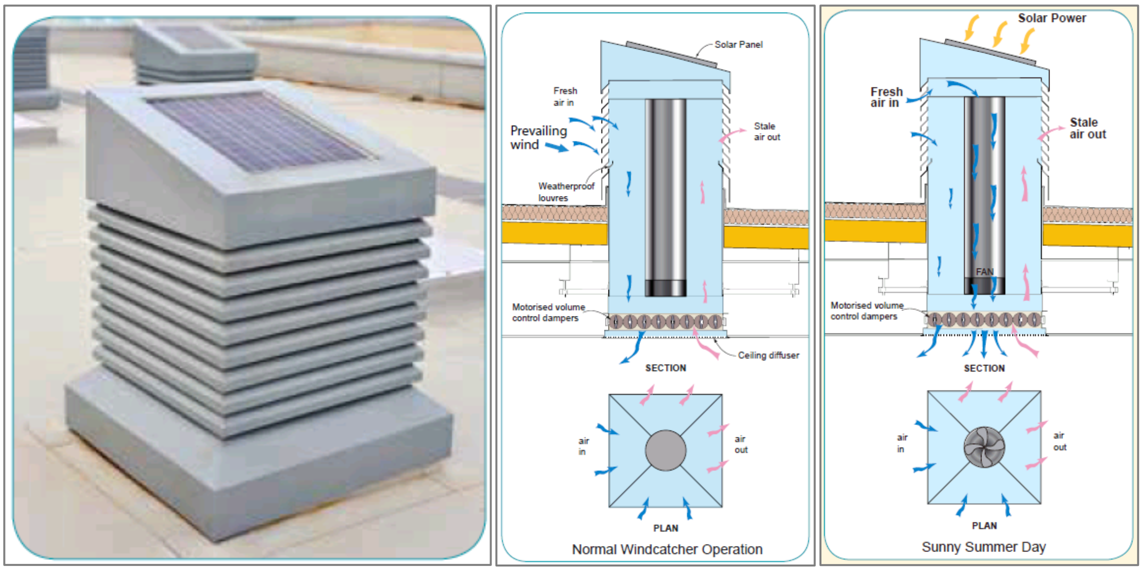


Figure 18 Modern bidirectional windcatcher.[14]

## 4.2. Ventilation chimneys

Ventilation chimneys are widespread and historically anchored elements of enhancing air flow, especially for ventilative cooling purposes. Chimneys make use of the hydrostatic buoyancy of air being warmer than its surrounding. Thus, chimneys are independent from wind, but rely on vertical extension and on temperature difference. The latter may be enhanced by additional heating and insulation, i.e. solar radiation (solar chimney).

The thermal buoyancy driving force of air roughly results in:

$$\Delta p = (\frac{1}{30})\Delta T h \tag{13}$$

*h* Static height between room and chimney exhaust [m]

*Δp* Buoyancy driven static pressure difference [Pa]

*ΔT* Difference between room temperature and mean air temperature in the chimney [K]

[14] https://www.monodraught.com/ (30/10/2017)

Buoyancy driven chimneys only perform in combination with low flow resistance ventilation systems. Furthermore, they may be combined with wind driven elements such as venturi shaped capping or may be effectively empowered by supportive electric exhaust ventilators. Ventilation chimneys may be added at the roofs of buildings or be constructed as internal ventilation shafts, an ideal solution for high rise buildings.

A special form of ventilation chimneys are solar chimneys, making additional use of solar radiation to enforce buoyancy. Solar force may double or triple the effect of a solely buoyant chimney. In cool climates the balance between the desirable effect of solar heat gains and the undesirable effect of transmittive heat loss has to be examined carefully. Special forms of solar chimneys are double skin facades, exposed to solar radiation and causing negative pressure to the adjacent rooms. Most of the ventilation chimneys used in buildings are tailor made (Figure 19).

Figure 19 Solar ventilation chimneys.[15]

## 4.3. Mechanical Ventilators

In principle, ventilative cooling may be supported by mechanical ventilators too. Their electrical efficiency has to be very high though, not to negate the effect of ventilative cooling.

Ventilative cooling typically operates at temperature differences between supply air and exhaust air of no more than 2-4 K, leading to a specific heat extraction of 0.7-1.4 W/(m³h). To reach an adequate efficiency ratio between heat extraction and power consumption of i.e. 10, the specific fan power must be limited to very low values of 0.07 W/(m³h) up to 0.14 W/(m³h), which equals 250 W/(m³s) to 500 W/(m³s).

[15] www.solaripedia.com (30/10/2017)

### 4.3.1. General qualities and specifications

***Air flow and pressure-increase***

The basic characteristic of a fan is its range of air flow and pressure-increase. This pair of key performance indicators is presented in performance curves, which are diagrams of pressure-increase as a function of airflow. For mechanically supported ventilative cooling applications, low pressure-drops are mandatory. Therefore only fans, with the capability of operating at pressure-increases lower than 100 Pa, are of interest to ventilative cooling. Some fan types require a minimum pressure-increase. Those are not recommended for ventilative cooling applications.

***Noise level***

Another key performance indicator is the noise level of a fan, given by the ‘A’ weighted sound power level. Manufacturers often indicate the noise level within the fan’s performance curves. The sound power level is usually measured at the fan outlet. The ‘A’ weighted sound power level at fan inlet results roughly by subtracting 3 dB(A) from the sound power level at the fan outlet. The ‘A’ weighted sound pressure level (LPA) at a distance of 1 metre is calculated approximately by deducting 7 dB(A) from this level.

***Efficiency***

Ventilator’s total efficiency consists of three components: the aerodynamic efficiency, the power transmission efficiency and finally the motor efficiency. Efficiencies of today’s EC motors in ventilators reach values beyond 85%. Most modern ventilators use direct drive technology, which eliminates losses of power transmission.

Thus, the total efficiency of ventilators depends on motor technology (EC motors highly recommended) and from the type, size and operating point of the ventilator. The total efficiency may reach values beyond 60% in case of centrifugal fans with backward-curved blades.

Within European Community obligatory minimum values of the total efficiency of ventilators are defined in European ecodesign requirements for fans (No 327/2011).

### 4.3.2. Axial fans

Amongst others, axial fans offer specific qualities, which are useful for ventilative cooling applications like high airflow at low pressure drops, wide control range, low noise, free flow capability (Figure 20). Axial fans offer medium levels of total effiency, ranging from 30% to 45%.

Figure 20 Modern axial fans. [16]

### 4.3.3. Radial fans

Radial fans are the most common type of fans used within air handling units. They are chosen for their wide range of airflow at medium to high pressure-drop, offering steep volume-pressure-curves and high efficiency-ranges. Still, a significant shortcoming in the case of ventilative cooling is the fact that most radial fans ask for a minimum pressure-increase, which easily reaches 100 Pa. This is acceptable within air handling units, with filters and heat exchangers, but is a contradiction to the characteristics of ventilative cooling. Still, radial fans offer best levels of total effiency, ranging from 45% to 65%.

An example of a radial fan is presented in the following Figure 21, showing a 2.1 kW fan of 450 mm impeller diameter, with backward curved impellers, designed for an airflow of 10000 m³/h at a pressure-increase of 60 up to 400 Pa.

Figure 21 Radial fan. [17]

[16] https://www.rosenberg-gmbh.com/en/product-range/fans/centrifugal-fans (30/10/2017)
[17] https://www.rosenberg-gmbh.com/en/product-range/fans/centrifugal-fans (30/10/2017)

### *4.3.4. Tangential fan*

Tangentials fans consist of a rotor which leads the air in tangential direction. Special qualities of tangential rotors is their compact shape, making them best choice for narrow spaces, such as decentral air handling units as well as heating/cooling convectors. Another strength is their low noise level. Tangential fans are designed for low pressure-increase up to 50 Pa, which is very much appropriate for ventilative cooling applications. As a shortcoming, radial fans offer low levels of total effiency, ranging from 15% to 25%.

An example of a radial fan is presented in the following Figure 22, showing a 72 kW fan of 80 mm impeller diameter, designed for an airflow of 400 m³/h at a pressure-increase of 60 Pa.

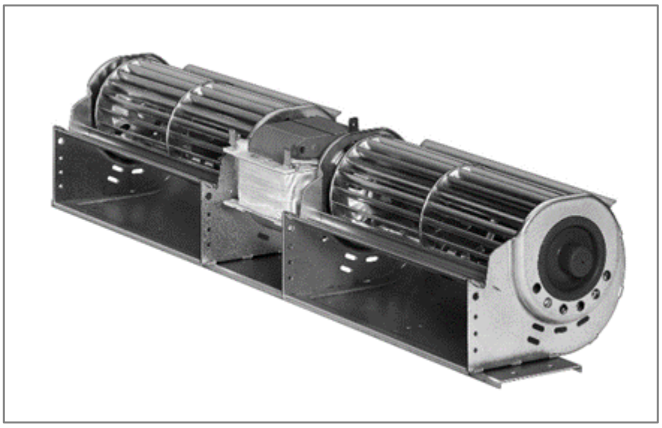

Figure 22 Tangential fan.[18]

## 4.4. References


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2) Saadatian O, Haw L.C, Sopian K, Sulaiman M.Y. Review of windcatcher technologies. Renewable and Sustainable Energy Reviews 2012;16(3):1477-1495.


[18] http://www.ebmpapst.com/de/products/tangential-blowers (30/10/2017)

# 5. Passive cooling ventilation components

In this chapter, components for passive cooling, as a possible extension of ventilative cooling, are presented.

## 5.1. Comfort ventilators

### *5.1.1. General aspects*

Air movement is the most effective mean of increasing the amount of heat transferred from the body, both by convection and evaporation. Thus, air movement, hereby addressed as comfort ventilation, is not a measure for extracting heat from a house but of extracting heat from a human body.

The effect of raising the personal neutral temperature by moving air is quantitatively described in many comfort Standards (i.e. ISO 7730:2005, Appendix G). The graph indicates the air speed needed to offset an elevated temperature. It is valid for light sedentary work of 1.2 met and for summer clothing of 0.5 clo. The set of curves indicates the correlation for specific temperature differences between the air temperature and the mean radiant temperature (Figure 23).

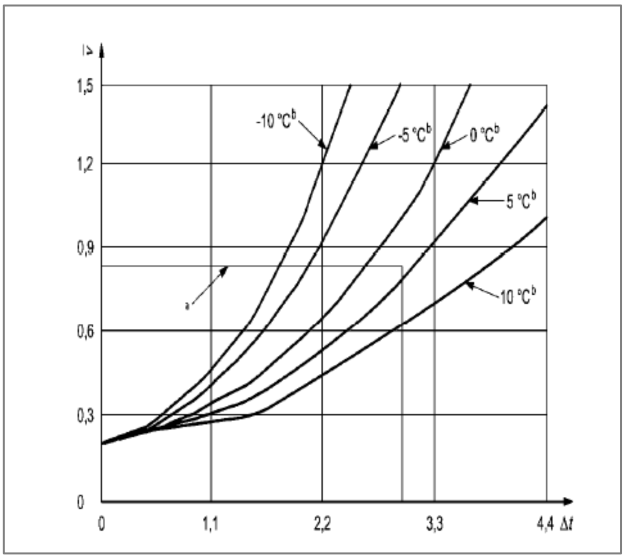


Figure 23 Thermal effectivity of comfort ventilation [1].

Air movement may be provided both by natural airflow and by mechanical fans. Box fans, oscillating fans or ceiling fans are well known and proven for increasing the interior air speed and improving thermal comfort. Higher air speeds permit the buildings to be operated at a higher set-point temperature and thus to reduce its cooling needs. Air circulation fans allow the thermostat to increase by >2°C. Thus, fans can contribute up to 40% of the cooling need of buildings under the assumption that the occupants are always close to the fan.

Regarding personal acceptability it is necessary to enable people to personally control comfort ventilation. Moving air of 1 m/s, which is the same speed as normal walking, may be regarded as a nice breeze, or as a nasty draft, all depending on the degree of personal adaptive options.

### *5.1.2. Ceiling fans*

Ceiling fans have dominated the US market (almost two out of three homes have at least one ceiling fan). If equipped with DC-motors, ceiling fans offer performance at very low energy consumption. Typical ceiling fans of 1.3 m diameter operate at 4-16 W, comfortably ventilating spaces up to 25 m².

A short calculation example illustrates the efficiency of comfort ventilation by ceiling fan compared to air conditioning: A ceiling fan, applied to an office room of 25 m² floor area, operated at medium power of 10 $W_{el}$, therefore 0.4 W/m² may cause a decrease of operative temperature by 2 K. With an estimated outside airflow rate of 5 m³/h per m² floor area, this results in an additonal thermodynamic cooling load of 3.4 W/m². With an estimated seasonal energy efficiency ratio (SEER) of the air-condition systems of 4.0 this results in 0.85 W/m², which is more than twice as much as the specific consumption of the ceiling fan.

Shortcomings of ceiling fans may be their overarching effect on the whole room and therefore on all persons within the room, eliminating the possibility of individual personal control. The height of the internal space is another constraint.

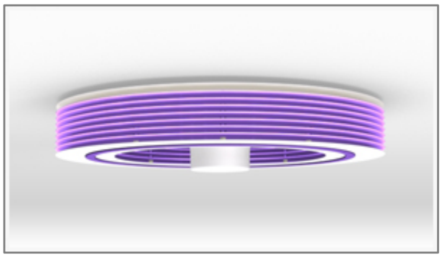

Figure 24 Bladeless ceiling fan.[19]

[19] http://exhalefans.com (30/10/2017)

Figure 25 High efficient 3-blade ceiling fan.[20]

### 5.1.3. Personal fans

The industry offers an enormous variety of personal fans. Apart from ceiling fans they share the advantage of individual personal adjustability. Experimental developments target personal convective cooling devices integrated into office furmiture, e.g. ventilated chairs.

## 5.2. Evaporators

### 5.2.1. General aspects

***Scope***

Evaporative cooling of buildings refers to a series of techniques that have been considered especially in hot-dry climates. This process uses the large heat absorption due to evaporation of water to reduce the dry bulb temperature (DBT) of inlet airflow (direct evaporative cooling-DEC) or to increase the heat sink potential of a building element to absorb internal heat (indirect evaporative cooling-IEC). Furthermore, an indirect sensible reduction of an inlet DBT may also be obtained by cooling the secondary airflow through direct evaporation in a sensible air-to-air heat exchange. This chapter focuses on ventilative cooling not considering the use of evaporative cooling to treat a liquid flow, e.g. in cooling towers.

[20] http://www.lampsplus.com (30/10/2017)

***Direct evaporative cooling functioning***

The DEC process is adiabatic and follows the relative constant wet bulb temperature (WBT) line on a psychrometric chart. Hence the theoretical minimal DBT that can be reached by direct evaporative treatment of airflows is the corresponding WBT and the potential of DEC can be described by the wet bulb depression (WBD), which is calculated as the difference between the DBT and the WBT. Several parameters influence the efficiency of DEC systems in treating airflows especially the forces inducing the natural airflow and the morphological parameters of the system. The former refers to the wind pressure on the inlet vent, the downdraught force due to the increase in specific air weight and the motion transfer between water drops and the airflow. The latter refers to the geometry of the DEC system (i.e. the tower height, the DEC typology, the type of nozzles and the aerodynamic behaviour of the system).

The following expression seems to be the most effective in estimating the outlet DBT of airflows after DEC treatment when the inlet air DBT and RH% are known:

$$DBT_{out} = DBT_{in} - \varepsilon\,(WBD_{in}) \tag{14}$$

*DBT* Dry bulb temperature [in or out; °C]

*WBD* Wet bulb depression [°C]

*ε* Slope coefficient (0.8)

A further expression to estimate the outlet DBT in a shower tower:

$$DBT_{out} = DBT_{in} - WBD_{in}\big(1 - exp(-\varepsilon h)\big)\big(1 - exp(-0.15WF)\big) \tag{15}$$

*DBT* Dry bulb temperature [in or out; °C]

*h* Tower height [m]

*WBD* Wet bulb depression [°C]

*WF* Water flow [l/min]

*ε* Slope coefficient (0.8)

### *5.2.2. PDEC tower typologies*

Even if current applications of evaporative cooling systems for ventilative cooling are mainly to be found in mechanical systems (i.e. desert cooler), passive solutions are also possible and principally refer to passive downdraught evaporative cooling (PDEC) techniques. Several technological strategies can be adopted in a PDEC tower:

- Wet pad is a system where the water is sprayed on a pad. This humid pad, which can be made from treated cellulose, is crossed by an airflow which acts as an evaporative exchanger. DEC wet pad systems are widely used and several commercial solutions are present on the market generally coupled with fans;

- Porous media are systems in which porous surfaces are maintained humid while exposed to an airflow which reduces its temperature due to evaporation. Several archetypes were present in traditional buildings in India, Greece, and Arab countries;
- Shower and misting towers work in similar fashion by using nozzles which are localized near the top of the tower and which spray directly in a vertical downdraught airflow. Depending on the type of nozzle used and the relative dimension of the water drops produced, a misting tower is different from a shower tower because of lower drop dimensions and higher water pressure to ensure a nebulization of the water in the airflow. Nebulizers and atomizers (misting tower) allow us to evaporate almost all the sprayed water especially if the amount of water varies according to environmental conditions. This may help avoid non-evaporated water collection, reduce the risk of bacteria formation in recirculating water, and reach the desired airflow DBT in a shorter tower height. On the other hand the shower or coarse tower may be used to both treat the air and the residual water by reducing their temperature.

### *5.2.3. Principal nozzle characteristics*

Nozzles are the main elements in direct evaporative cooling (DEC) systems, especially for shower and misting towers. Several typologies of sprayers are present on the market, principally for pressurized water flows using pumps. The main characteristics of a nozzle are:

- the level of pressure which can range from that of an aqueduct to the very high pressure levels of industrial systems;
- the amount of sprayed water in a unit of time at a given pressure;
- the spray angle or the coverage at a given height;
- the size of water droplets at a given capacity (the amount of water flow at a given pressure);
- the type of cone: full cone, hollow cone, semi-full cone, flat spray or air atomizing;
- the shape: i.e. round or squared;
- the number of orifices: single or multiple;
- the technology used: pressure, turbulence, deflection (i.e. spiral nozzle) or atomization with compressed air.

Furthermore, other nozzle characteristics to be considered are the material used, the end connection, the impact force (generally not mentioned), and the lifespan or nozzle wear (generally not mentioned) which depends on the material used.

### *5.2.4. Building integration strategies*

Three main passive downdraught evaporative cooling (PDEC) integration choices may be defined according to the position of the tower:

- Internal tower, both open and closed: a PDEC tower installed inside the building - i.e. in an atrium, an existing shaft, or a skylight well - which is able to treat the air in an open (open internal tower) or closed space - e.g. rooms, offices - connected through air vents. When a shower tower is considered, a sufficient distance between the first air vent and the nozzles has to be allowed in order to have a satisfactory effect;

- External adjacent tower: a PDEC system attached to a building façade. It can serve one or more spaces which are connected by air vents or ducts;
- External detached tower: a detached tower installed near the building and connected through horizontal connections with the building itself (i.e. large buried channels). This solution may be considered if one tower is used to treat a large amount of air.

### 5.2.5. Climate applicability and limitations

The applicability of a PDEC system can be principally limited by local wet bulb depression (WBD), lack of specific knowledge/companies, the need for access to local water and the risk of creating microorganisms in the water such as bacteria, fungi, and algae (i.e. legionella). Especially to prevent bacteria formation several strategies must be adopted. For PDEC towers additional considerations:

- Water temperature has to be controlled because it affects bacteria formation especially when it rises over 20°C but remains under 60°C;
- The use of biocides is highly recommended together with water filtering to reduce the amount of possible nutrition particles;
- A correct choice of nozzles may help to reduce the amount of water directly sprayed onto the tower's internal surfaces by controlling the sprayer angle. This also allows us to avoid non-evaporated water precipitation outside the collection basin at the bottom of the tower;
- In open atrium applications, people must be protected from direct exposition to the water flow. The adoption of drift eliminators to reduce the amount of non-evaporated water drops from the outlet airflow may also be considered.

The suitability of evaporative air conditioning systems in different parts of the world was also mapped by the World Bank in the Technical Paper No. 421 [2].

Furthermore, the ventilative cooling potential tool, developed during the work of Annex 62[21], includes an analysis of the number of hours during which DEC systems may potentially reduce discomfort even if direct ventilation alone may not be considered a useful solution due to initial high environmental air temperature.

[21] http://venticool.eu/annex-62-publications/deliverables/ (30/10/2017)

## 5.3. Phase change material

### *5.3.1. General aspects*

Phase change materials (PCMs) are capable of storing and releasing thermal energy during the process of liquefaction and solidification (changing phase), making them ideal for thermal management applications. Figure 26 displays the theoretical performance of a PCM. The latent thermal energy transfer takes place when the phase change occurs. Under the heating cycle, the PCM will perform in the same way as sensible storage materials would with temperatures rising as the heat is absorbed. When the PCM reaches its melting point it changes phase and absorbs large quantities of heat without rising in temperature, then when it has fully melted it will once again act as a sensible heat storage system. The (reverse) freeze cycle of the PCM takes place when the temperature of the medium surrounding the material decreases. When the temperature of the PCM reaches its freeze temperature it solidifies, releasing the latent heat it had stored during the melt cycle. Throughout this cycle PCMs absorb and release thermal energy whilst maintaining a nearly constant temperature. PCMs may be classified into 3 main categories; organic, inorganic and eutectic materials, as shown in Figure 27.

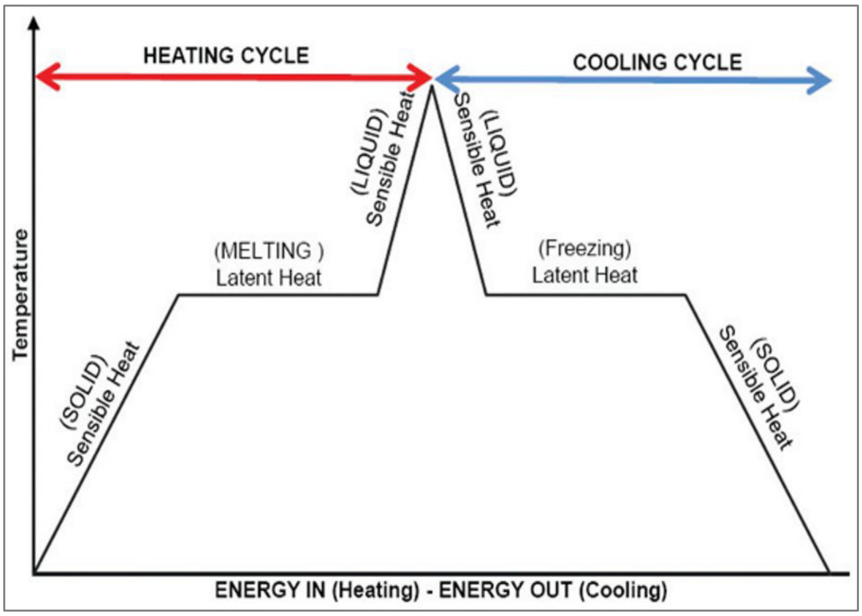


Figure 26 Theoretical performance of a PCM [3].

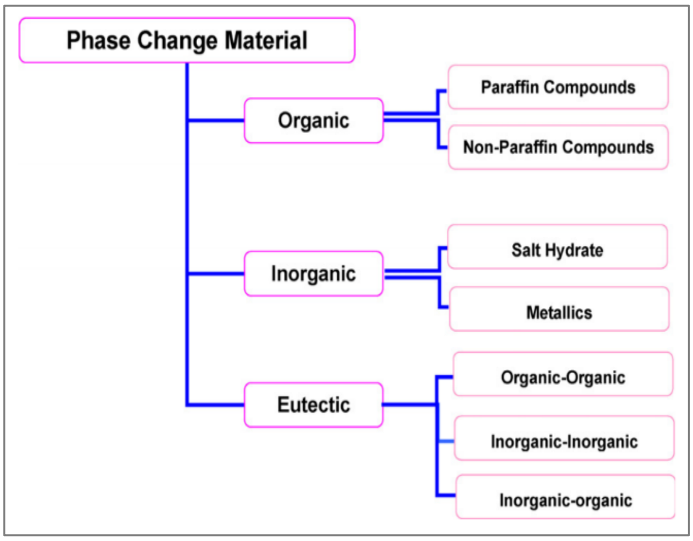


Figure 27 Classification of phase change materials [4].

### *5.3.2. PCMs in ventilation systems and research results*

PCMs can be employed into the building envelope or be integrated with the ventilation system providing passive cooling. During the night, cool external air is passed over the PCM with the aim of achieving its solid state (freeze cycle). During the day, as internal air temperatures rise, the warm air is passed over the PCM which absorbs thermal energy, turning back from a solid to a liquid (melt cycle) and thus cooling the air.

Recent reviews suggest that although there have been a large number of theoretical and numerical studies conducted on the application of PCM integrated into ventilation system and systems have been installed in operational buildings, there is a lack of data on actual performance of PCM integrated in real life buildings and actual case studies are essential to document performance as well as address cost savings.

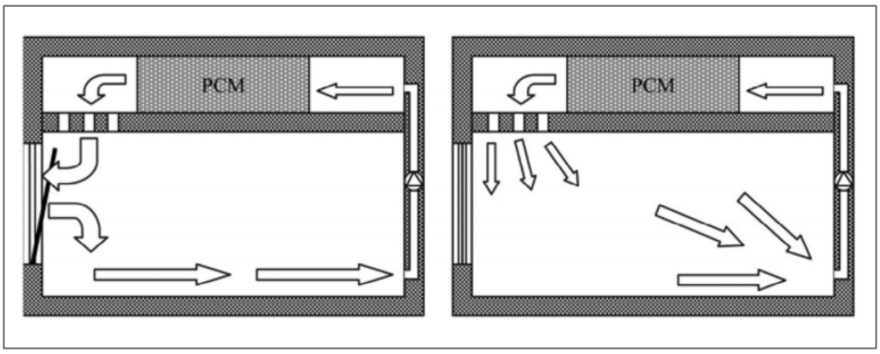


Figure 28 Function of PCM free cooling system. Left: Night Operation, Right: Day Operation [5].

A ventilation system with PCM thermal battery known as 'Cool-Phase' is marketed by Monodraught Ltd in the UK[22]. The system is concealed in the false ceiling and its appearance to the user is that of a conventional ventilation system with supply and extract terminals. Air is drawn from outside or the room using a variable speed fan. During operational hours and depending on internal air quality (monitored through $CO_2$ sensors) the air is mixed with recirculated air from the room to conserve energy. The air is then directed through the PCM thermal battery to be cooled if necessary (determined by air temperature sensors and control rules) or by-passes it if cooling is not needed. Outside operational hours, ambient air is used to recharge the PCM thermal battery the duration of which is determined by air temperature sensors and control rules according to the season (Figure 29).

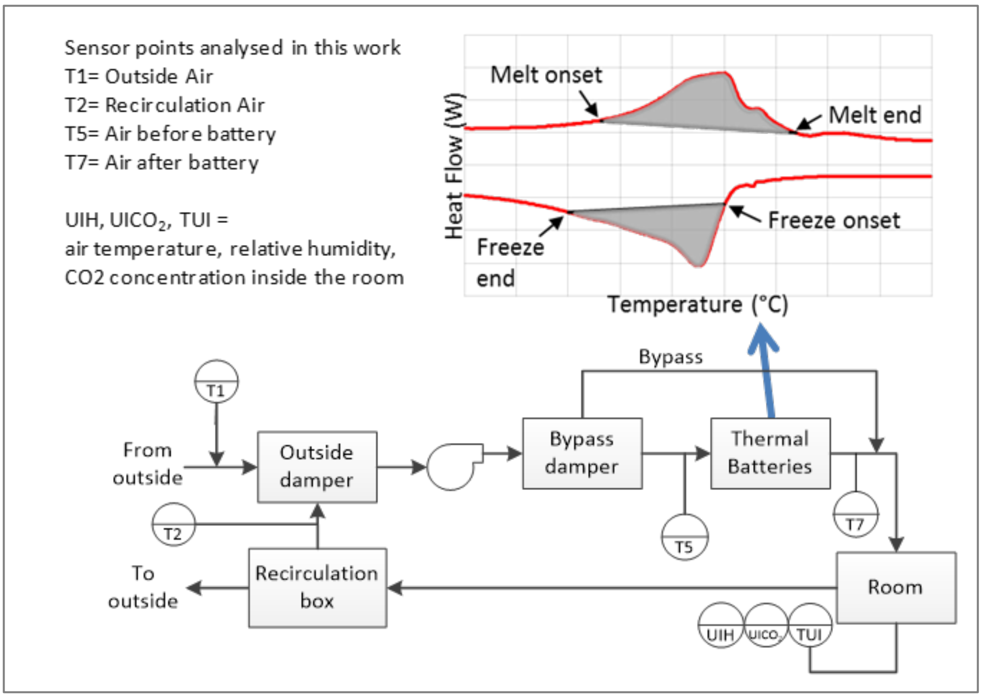


Figure 29 Cool-Phase scheme with an explanation of the PCM thermal battery operation principle [5].

## 5.4. References


1) International Organization for Standards. ISO 7730: 2005. Ergonomics of the thermal environment. Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. Geneva: ISO; 2005.


[22] https://www.monodraught.com/products/natural-cooling (30/10/2017)

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# 6. Automation components

In this chapter, components of the automation system are presented.

## 6.1. Actuators

The core issue regarding actuation in ventilative cooling is opening and closing ventilation elements, such as windows, doors, flaps, dampers, louvres and others. There is an immense variety of actuators available. Roughly they may be structured into linear actuators, chain actuators, folding actuators, rotary arm actuators and rotary actuators.

The main criteria for chosing from the wide variety offered, are:

- Stroke
- Force
- Space needed and visual appearance
- Water protection / Insulation class
- Sound emission
- Durability, robustness

### *6.1.1. Linear actuators*

Linear actuators consist of solid tubes or prisms, with a push-rod, driven by an electric motor via a spindle or rack. They are in general robust and durable. They allow high opening strokes up to 1,000 mm and more. They offer significantly high opening and closing forces up to 500 N, in the case of heavy-duty types even up to 1,000 N. Most linear actuators are operated at voltages of 230 V or 24 V. Typical operating speeds are in the range of 2 cm per second. Linear actuators are commonly used for domes, smoke exhaust flaps and for high level windows which are out of reach from persons. Rack actuators are especially suitable for connecting two or more actuators to one motor-shaft, securing precise synchron movement of both actuators. A limiting factor is their special form. Linear actuators use significant space in front of the window and may cause injury if used in occupied zones with children, elderly people or pets.

Figure 30 Electric linear actuator.[23]

### 6.1.2. Chain actuator

Chain actuators deliver a pushing steel chain instead of the pushing rod, again driven by a 230 V or 24 V electric motor via a sprocket. Chain actuators offer the benefit of slim construction without the disadvantage of the rod casement compromising the use of the adjacent space. Thus, they are commonly used for windows which are accessible by people, both top hung, side hung and also roof vent windows.

In comparison to linear actuators chain actuators offer the big advantage of small dimensions but are comparably limited in stroke and force. Typical strokes reach 400 mm, while typical push and pull forces reach 300 N. Heavy duty chain actuators are constructed with a double chain for higher stability, offering strokes up to 1,000 mm and forces up to 600 N.

Figure 31 Chain actuator.[24]

### 6.1.3. Folding and rotating arm actuator

Folding actuators and rotating arms are both suitable for top and bottom as well as side-hung windows. Opening angles even beyond 90°.

[23] http://www.ultraflexgroup.com/en/catalogue/electric-linear-spindle-actuators (30/10/2017)
[24] http://www.ultraflexgroup.com/en/catalogue/electric-chain-actuators (30/10/2017)

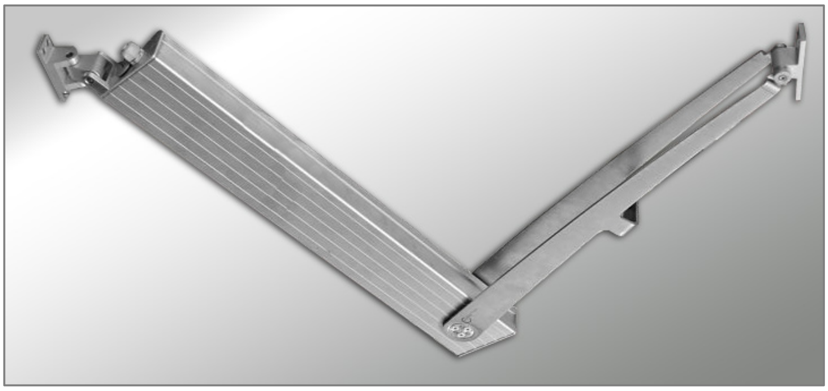

Figure 32 Folding and rotating arm actuator.[25]

## 6.2. Sensors

Good operation and performance of the ventilative cooling system requires a robust control. This control strategy is defined by using conditions which are measured inside and outside the room. Therefore, accurate sensors are needed that meet the following requirements:

- Trustworthy accuracy inside operating range
- Sufficient measurement/operating range
- High precision and reproducibility
- Fast response time
- Linear output signal, with minimal linearity deviation and low hysteresis
- Correct output signal
- High stability sensor for a period of at least 5 years (no recalibration needed-or automatic recalibration)
- No interference with other sensors
- Sufficiently stable output signal with minimal noise
- Low cross-sensitivity to any other property and influencing factors

This chapter gives an overview of the most common parameters and sensors used in controlling ventilative cooling.

### *6.2.1. Parameters*

First, the relevant parameters for controlling the ventilative cooling system are defined. For the ventilative cooling system the following parameters are relevant to control the system:

- Room temperature: This parameter is important to control the ventilative cooling system;

[25] http://www.simon-rwa.com/en/brandschutz-produkte/smoke-and-heat-exhaust/actuators/folding-arm-actuators.html (30/10/2017)

- Relative humidity: This parameter is important in humid climates or for special rooms e.g. bathrooms. When outdoor air is introduced into the room the relative humidity will be affected therefore it is important to monitor the relative humidity;
- $CO_2$ concentration: This parameter can be used during occupancy to control the indoor air quality (IAQ). $CO_2$ is mainly produced by occupants inside a room, so it gives a good indication of the number of occupants;
- Occupancy: This parameter measures if occupancy is detected within a predefined range.
- Indoor air velocity: To reduce the draught rate caused by ventilative cooling indoor air velocity can be measured.

In addition to these environmental parameters weather data (like outdoor air temperature, relative humidity, wind direction and wind speed) will be used for controlling the ventilative cooling system. This data can be obtained from a local weather station.

### 6.2.2. Typology

For each parameter different types of sensors are available on the market. However, each type of sensor has a different application.

***Temperature***

Three types of sensors are available to measure room temperature. Regarding costs the prices for each sensor are comparable. Thermistors and resistance temperature devices (RTD) deliver the highest accuracy possible but have a slower response time compared to a silicon temperature sensor. Silicon temperature sensors are found in most temperature sensors which are used in rooms to control the heating or ventilation system since they are easy to implement and are digital. Accuracy is poorer compared to other sensors, however, for controlling the system it is sufficient [1].

***Relative humidity***

For relative humidity a capacitive polymer or a ceramic resistance can be used. Both type of sensors have a comparable accuracy and response time. The main difference is the measuring range for both sensors. Both sensors are available wired and wireless [2].

***$CO_2$***

$CO_2$ concentration inside buildings is measured by nondispersive infrared (NDIR) sensors which offer a good accuracy [3]. These sensors are available both wired and wireless where the wireless sensors are more expensive. Reaction time is usually around 30 seconds. Still these sensors are expensive compared to temperature and humidity sensors. For $CO_2$ an accuracy of ±50 ppm in the range of 400-2000 ppm is recommended. Recalibration for the sensors is advised at least every 5 years.

***Occupancy***

For occupancy two techniques can be used to detect if people are inside a room or not. The passive infrared (PIR) detects if persons are inside a predefined range of the sensor. If people are too far from the sensor no presence is detected. The ultrasonic sensor is more accurate, since they do not use a fixed field of vision. The function of this type of sensor is based on the Doppler effect. However, the better detection results in higher costs of the sensor.

***Indoor air velocity***

For indoor air velocity a hotwire or a hot film sensor can be used. A hot film sensor is more robust compared to the hot wire sensor. However, the measuring range and accuracy is less precise to make it less suitable for indoor air velocity measurements. Indoor air velocities are low especially in occupied zones, most of the time measurement values are below 0.20 m/s. Both sensors are relative expensive compared to the sensors for other parameters [3].

### *6.2.3. Characteristics*

The characteristics determine the performance of the ventilative cooling system since they are used to control the system. Furthermore the sensors used for a ventilative control are listed in Table 3 in which the important properties are summarized.

The sensors listed in Table 3 are widely used within buildings. Most sensors are also used to control heating/cooling or ventilation systems.

***Accuracy***

Accuracy determines the precision of the measured data. Before the installation of the sensors of a ventilative cooling system the level of accuracy needs to be determined. The claimed accuracy of a sensor may not be available over the whole operating range. Furthermore, the accuracy can be affected by the stability of the sensor, hysteresis or environmental variables [1].

***Response time***

For operation and control of the ventilative cooling system the response time of the sensors is of importance. With a fast response time the system can control more stable and accurately the actual demand inside the room [1].

***Communication***

Nowadays most sensors are also available as wireless versions, however this will result in extra costs compared to wired sensors. Important for wireless sensors is the wireless setup to avoid interference with other measurement signals and to assure the coverage [3].

***Measuring range***

It is important to have a sensor that can operate inside the complete measuring range. This is to avoid measurement errors due to measurement values outside of the operating range of the sensor.

***Positioning of sensors***

For performance of the ventilative cooling system the positions of the sensors installed is important. Measurement errors due to a poorly chosen measurement position must be avoided. For positioning of the sensors it is important to have no direct sunlight on the sensor. Furthermore, sensor positions near a door or window should be avoided to reduce measurement errors due to increased air flow. Finally, the sensor should not be located near an air supply to decrease the impact of fresh supply air [4].

Table 3 Type of sensors available for each parameter for control of ventilative cooling systems [1-5].

| Measured parameter | Type of sensor | Accuracy | Response time | Communication technology | Cost (US$) | Measuring range |
|---|---|---|---|---|---|---|
| Room temperature | Thermistor | ±0.1-0.5°C | 10-30 sec | wired-wireless | 20-70 | -50-180°C |
| | RTD | ±0.15-0.6°C | 25-60 sec | wired-wireless | 35-100 | -50-100°C |
| | Silicon temperature sensor | ±0.50 | 1-60 sec | wired-wireless | 10-100 | -50-150°C |
| Relative humidity | Capacitive polymer | ±2-4.5% | 10-50 sec | wired-wireless | 50-200 | 0-100% |
| | Ceramic resistance | ±2-5% | 10-50 sec | wired-wireless | 40-150 | 10-90% |
| Indoor air velocity | Hotwire | ±2-5% of reading | 0.2-5 sec | wired | 500-1800 | 0.05-20 m/s |
| | Hot film | 0.2 m/s + 3% measurement value | 4 sec | wired | 500-1800 | 0.2-10 m/s |
| $CO_2$ concentration | NDIR | ±30-80 ppm | 30-50 sec | wired-wireless | 200-500 | 0-2000 ppm |
| Occupancy | PIR | 3-5 m radius or 5-12 m front and 3-8 m lateral | 10 sec-15 min | wired-wireless-standalone | 25-80 | |

| | | | | |
|---|---|---|---|---|
| Ultrasonic | 185 m2 | 30 sec-30 min | wired-wireless-standalone | 150-300 |

## 6.3. Controllers

### *6.3.1. Local controllers*

In case of singular automated ventilation openings in small and medium residential applications, local control of automated ventilation openings might be an appropriate option. To minimize installation efforts, manufacturers offer wireless solutions together with smart home controllers. Input variables may be temperature, humidity, $CO_2$ and time.

### *6.3.2. Central controllers*

In most cases of large residential as well as commercial ventilative cooling applications central control will be the best option.

Ventilative cooling may be integrated in the building's central Direct Digital Control (DDC). Input parameters may be again indoor temperature, humidity, $CO_2$ and time (outdoor temperature, wind, solar radiation).

It is important to clarify the control needs of ventilative cooling components already at the early design stage. Though, DDC in principle is open to all kinds of algorithms. Professional DDC solutions are predefined and limited in many aspects. Alterations of systems once installed may turn out impossible or expensive.

Attention has to be paid to the fact that ventilative cooling applications have to be parameterized during commissioning. Thus, many setpoints and control parameters have to be made adjustable for educated users and not for specialized programmers.

Furthermore, attention has to be paid to ventilative cooling's need for a variety of derived variables: Temperature might need to be converted to a mean value, or to a weighted mean value. Solar radiation might need to be transformed to radiation for a specific orientation. Very often time lags have to be included into decent ventilative cooling operation.

### *6.3.3. Entrapment Protection*

Entrapment protection is a topic of growing importance within ventilative cooling applications. It is a part of responsible designs and is mandatory in many countries. Especially for children or people with reduced attention and response capacity this is of great importance and mandatory in case of accessible windows or openings with automatic control without visual contact. In some countries, entrapment protection already is an issue of standardization.

The following options may be considered:

***Protection by pictograms***

A cheap but weak way of protection is placing pictorgrams near the automated openings, warning people. This may be a first step, but is far from sufficient.

***Protection by ineaccessibility***

Placing openings in parts of the wall or roof that are not accessible to anyone apart from service technicians is a suitable and comprehensive measure of protection, as long as the inaccessibility can physically be guaranteed. It is definitely not enough to just define the inaccebissility by prohibition or pictograms.

***Protection by injury preventive construction***

Protection by injury preventing construction is an appropriate option for many specific ventilative cooling elements such as grilles, dampers, terminals. Many of those industry products are designed according to the principles of injury prevention, securily protecting mechanical parts from accessability.

***Pressure sensitive sealings***

There are windows and ventilation flaps available, which are equipped with electronically pressure sensitive sealings, being connected to the window's actuator control. The window actuator stops operation, if a signal from the pressure sensitive sealing is sent to the control. In addition to just stopping the actuator from closing it is necessary to automatically re-open for some seconds, to release fingers that might have already been trapped. Pressure sensitive sealings offer a high safety level, but are generally expensive and need frequent maintenance of the sealings with silicon or similar.

***Infrared movement sensors***

Today infrared movement sensors offer a good choice for entrapment protection. Infrared movement sensors are relieable industrial standard products at reasonable prices. In case of solely night ventilation the window automation system could very efficiently and cost-effectively be connected to the same movement sensors which operate the lights.

## 6.4. References


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2) American Society of Heating Refrigeration, and Air-Conditioning Engineers. Handbook of fundamentals. Atlanta: ASHRAE; 2001.

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5) European Committee for Standardization. EN 13182: 2002. Ventilation for buildings. Instrumentation requirements for air velocity measurements in ventilated spaces. Brussels: ECS; 2002.

# 7. Glossary of national Annex 62 research projects

**Diffuse ceiling ventilation**
Per Heiselberg, Aalborg University, Denmark

**Perception of a cooling jet**
Hannu Koskela, Turku University of Applied Sciences, Finnland

**Investigation of ventilation system with PCM thermal storage**
Maria Kolokotroni, Brunel University, UK

**Ventilative cooling in Norwegian schools and kindergardens**
Maria Justo Alonso, Norwegian University of Science and Technology, Norway

**Ventilative cooling using a slot louvre system in a low energy building retrofit application**
Paul O'Sullivan, Cork Institute of Technology, Ireland

**Ventilative cooling in energy renovated single-family houses in temperate climates**
Theofanis Psomas, Aalborg University, Denmark

**Living lab: Hybrid and natural ventilation**
Maria Justo Alonso, Norwegian University of Science and Technology, Norway

**Ventilative cooling and energy use in frozen food supermarkets**
Maria Kolokotroni, Brunel University, UK

**Thermal comfort modeling and simulation in naturally ventilated low energy retrofits**
Adam O' Donovan, Cork Institute of Technology, Ireland

**Ventilative cooling on the test bench**
Peter Holzer, Institute of Building Research and Innovation, Austria

**Control strategy of housing components for ventilative cooling**
Toshihiro Nonaka, Lixil Corporation, Japan

**International ventilative cooling application database**
Theofanis Psomas, Aalborg University, Denmark

## 7.1. Diffuse ceiling ventilation

### 7.1.1. Abstract

A new system solution for natural cooling and ventilation of low energy office buildings has been developed. The solution can efficiently provide ventilation and cooling both in the winter period, where cold outdoor air can be used directly to cool down office spaces without creating draught, as well as in the summer period, where natural night cooling and thermal mass activation either passively or actively provides the cooling need.

The solution eliminates the need for electricity for air transport, optimizes the whole year cooling potential of outdoor air and utilizes the building thermal mass effectively without sacrificing the acoustic performance of the building.

The project results include development of system solutions and recommendations on their application areas and energy saving potential, determination of ventilation and cooling capacity and of the influence of key design parameters on system performance. The results are summarized in a design guide for diffuse ceiling ventilation.

### 7.1.2. Objectives

The project objectives included development of a new system solution, that combined natural ventilation, diffuse ceiling supply and thermally active slabs to provide buildings with an energy-efficient natural cooling solution.

### 7.1.3. Methodology

The project included theoretical analysis of application areas and expected performance. Energy performance analysis were carried out by dynamic thermal simulation on a typical office and a classroom building case. The cases were constructed according to Danish near zero energy building requirements. Analysis of expected thermal comfort and draught risk analysis were carried out by computational fluid dynamics (CFD) prediction. Documentation of energy and indoor environmental performance was carried out through full scale experimental lab studies. Finally, a design guide was developed based on literature review and project results.

### 7.1.4. Results

To analyze the energy saving potential a series of numerical analysis by dynamic thermal simulation was performed and results compared with performance of typical HVAC solutions.

To investigate the performance in relation to thermal comfort and draught risk a series of experiments were carried out in a lab set-up with and without air supply through a diffuse ceiling. Figures 33-34 show the set-up as well as an example of obtained results.

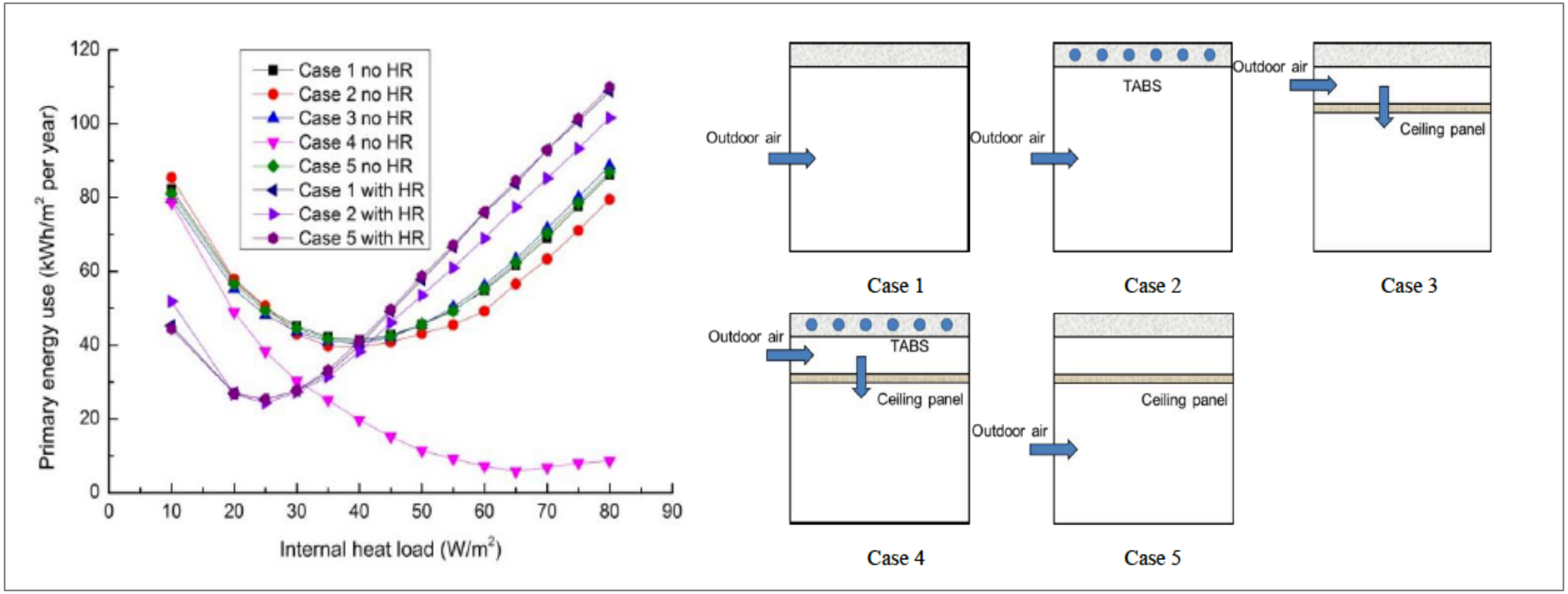


Figure 33 Primary energy use per year for heating, cooling and ventilation for the investigated cases. Case 4 represents the developed solution. HR stands for heat recovery.

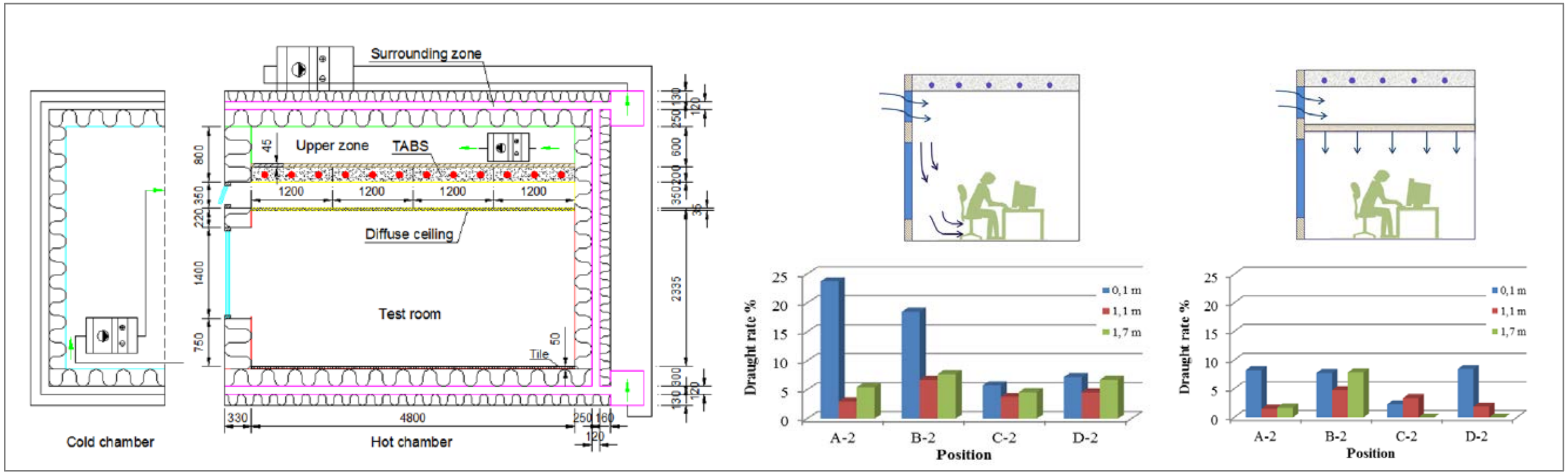


Figure 34 Full scale test chamber. Measured draught risk for an air change rate of 4 $h^{-1}$ and an air supply temperature of -4°C with and without air supply through a diffuse ceiling.

### *7.1.5. Conclusion*

A new system solution for natural cooling and ventilation of low energy buildings has been developed. The solution can efficiently provide ventilation and cooling both in the winter and summer period.

### *7.1.6. References*

Yu T, Heiselberg P, Lei B, Pomianowski M, Zhang C. A novel system solution combining natural ventilation with diffuse ceiling supply and thermally activated building constructions for cooling and ventilation in office buildings: a review of applied technologies and a case study. Energy Build 2015;90:142-155.

Zhang C, Heiselberg P, Pomianowski M, Jensen R. Experimental study of diffuse ceiling ventilation coupled with a thermally activated building construction in an office room. Energy Build 2015;105:60-70.

Zhang C, Yu T, Heiselberg P, Pomianowski M, Nielsen P. Diffuse ceiling ventilation: design guide. Aalborg: Aalborg University; 2016.

## 7.2. Perception of a cooling jet

### *7.2.1. Abstract*

The effect of a cooling jet from ceiling was studied in warm office conditions with human subject experiments in laboratory conditions. The perception was investigated with questionnaires and the participants were also carrying out different tasks measuring their work performance. Two test cases were studied: a constant velocity jet and an adjustable velocity jet. The thermal sensation as well as the acceptability of themal conditions improved notably with the jet. These results can be utilized in the development of energy-efficient air conditioning systems for offices where overheating occurs. However, individual control is needed, not only on airflow, but also on the direction of the jet.

### *7.2.2. Objectives*

The objective was to study the perception of a local cooling jet from ceiling and the effect of different parameters on the perception. This type of technical solution would enable lower cooling demand as well as local and personal control of thermal conditions in open-plan offices.

### *7.2.3. Methodology*

The study was carried out in laboratory conditions as human subject experiments with a room temperature of 29.5°C. The perception is studied with questionnaires. The subjects were sitting at a workstation carrying out different tasks which measured their work performance (accuracy and reaction time). The first study was done using a constant velocity jet with a maximum target velocity of 0.8 m/s. In the second study, the participants were allowed to adjust the jet target velocity between 0.3 and 1.5 m/s.

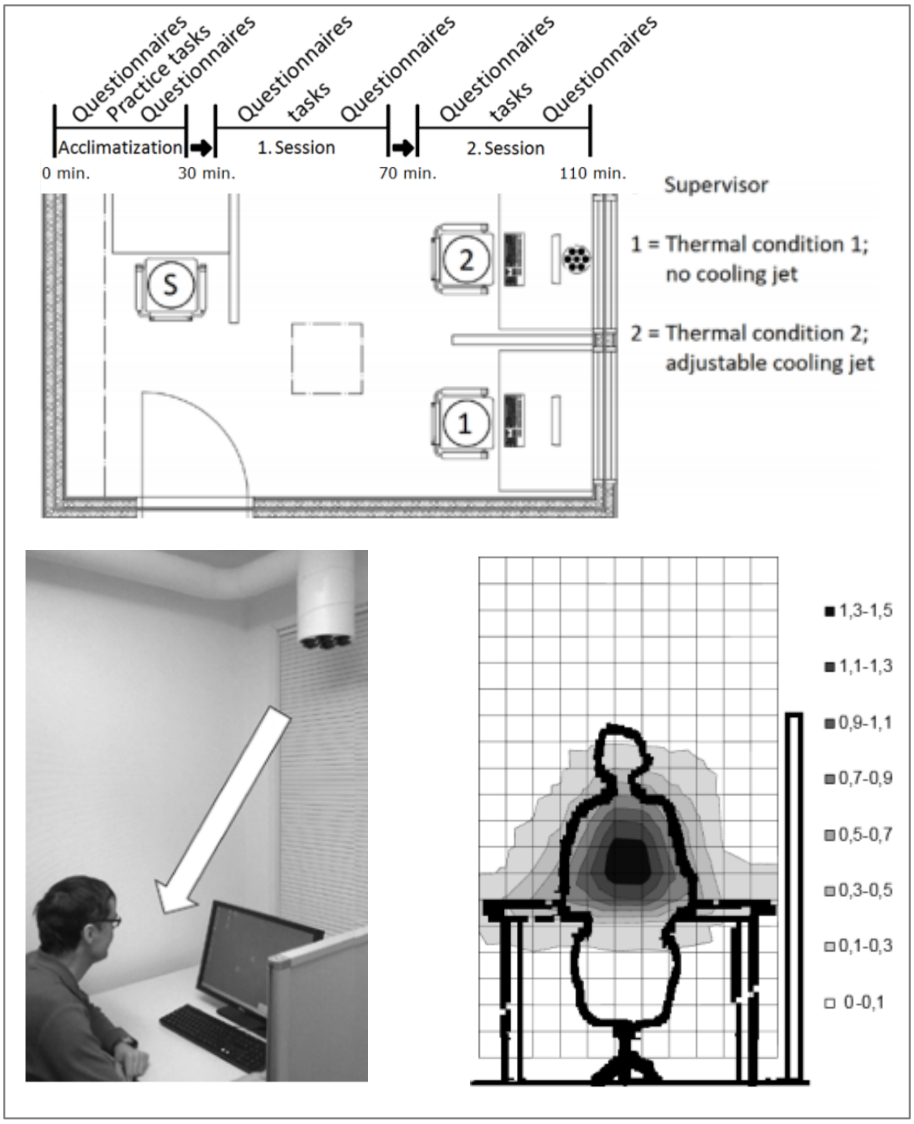


Figure 35 Test conditions and procedure in the laboratory.

### *7.2.4. Results*

With the constant velocity jet, 67% of the participants were dissatisfied with the thermal environment without the cooling jet, while only 28% were dissatisfied with the jet. With the adjustable jet, the corresponding percentages were 72% and 22%. Most of the participants (65%) adjusted the speed of the jet so that at the end of the session the target velocity was 1.1-1.3 m/s.

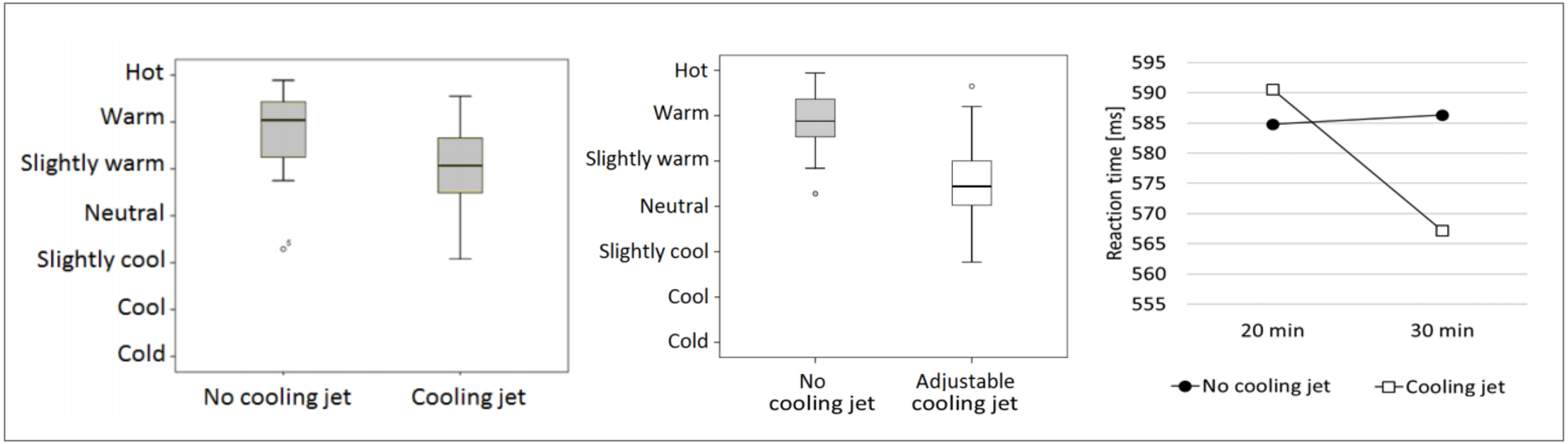


Figure 36 The distribution of whole body thermal sensation votes with and without the cooling jet with constant velocity jet (left) and adjustable jet (middle) and the effect on the cooling jet on reaction time (right).

### 7.2.5. Conclusion

The results suggest that providing local cooling with a ceiling based jet can improve thermal comfort, perceived indoor air quality and perceived working conditions in warm office environment. Additionally, symptoms, subjective workload and cognitive fatigue can be reduced with cooling jet. These findings can be utilized in the development of energy-efficient air conditioning systems for offices where overheating occurs. However, it seems that individual control is needed, not only on airflow, but also on the direction of the jet. In future, the effect of individual control on both the jet airflow rate and flow direction in otherwise similar conditions should be studied.

### 7.2.6. References

Maula H, Hongisto V, Koskela H, Haapakangas A. The effect of cooling jet on work performance and comfort in warm office environment. Build Environment 2016;104:13-20.

Maula H, Koskela H, Haapakangas A, Hongisto V. The effect of adjustable cooling jet on thermal comfort and perception in warm office environment-a laboratory study. Air Infiltration and Ventilation Center: Proceedings of 38th AIVC Conference, Nottingham, UK. AIVC; 2017.

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Maula H, Koskela H, Varjo J, Hongisto V. The effect of a ceiling based cooling jet on work performance and thermal comfort-A laboratory study. Proceedings of Healthy Buildings 2015 Europe Conference, Eindhoven, Netherlands. 2015.

# 7.3. Investigation of ventilation system with PCM thermal storage

### *7.3.1. Abstract*

This project investigated computationally and experimentally design solutions of an encapsulation to enhance heat transfer in PCM-air heat exchangers by examining the geometry of encapsulation and stacking density in relation to pressure drop and cost.

### *7.3.2. Objective*

Design a panel surface able to enhance heat transfer efficiency of PCM-air heat exchangers where cost of production and pressure loss is an important parameter for systems requiring low power demand and noise levels. Manufacture the optimised design and carry out tests in an experimental rig to assess its improved performance.

### *7.3.3. Methodology*

Analysis of monitored data in two buildings with a mechanical ventilation system with active PCM indicated that (a) internal air temperature is maintained within adaptive thermal comfort limits, (b) acceptable IAQ (indoor air quality) is maintained and (c) energy costs are low compared to AC buildings. One of the buildings has been analysed in detail to form a case-study of subtask C. The analysis also indicated that changes in the control strategy can improve performance, but this is limited by the PCM cooling capacity. One solution is to increase the PCM material resulting to larger space requirements. Another solution is to increase the heat transfer rate; this project investigated this solution numerically and experimentally by examining the geometry of encapsulation and stacking density in relation to pressure drop and cost of production. CFD simulations were conducted to assess turbulent forced convection heat transfer and pressure drop through a ventilation channel using a stack of panels with different ridge configurations. First, an experimental rig using an existing commercial panel provided by a PCM manufacturer validates the CFD model. After that, 3D simulations with different designs were tested until the optimum configuration in terms of heat transfer and pressure drop was achieved. The optimum design by geometry and performance was drawn in 2D and an analysis was performed by varying the spacing between ridges, height and ridge radius to identify difference in heat transfer performance.

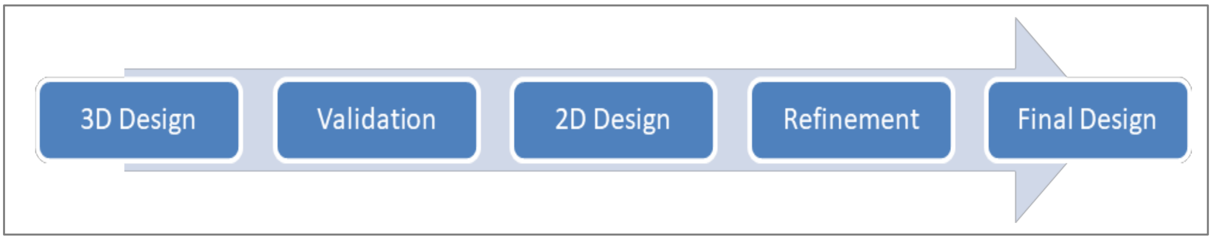


Figure 37 Design methodology.

### *7.3.4. Results*

When compared with a flat and existing commercial panel, results show that the inclusion of ridges increase the Nusselt Number by 68 and 93% respectively at a Reynolds number of 21600. At a Reynolds number of 18736, the Nusselt number of the optimum panel is enhanced by 64 and 111% when compared to the flat and existing commercial panel, respectively. This panel was then taken forward to allow further refinements which include changes in panel thickness and number of panels per module. Based on CFD simulations, a new design is proposed which reduces the number of panels per module from 9 to 6, reduces production costs but keeps nearly the same heat flux and pressure drop as the existing commercial panel. When seven panels are used, it is possible to hold 13.6% more material with an increased pressure drop 3.36 times higher than the existing commercial panel (176.80 against 52.69 Pa) at a Reynolds number of 18736. To assess the best design, the Nusselt number of all simulations were calculated and compared with a smooth surface. Calculations indicate that the inclusion of ridges favoured heat transfer by the increase of turbulence at lower Reynolds number allowing a reduction in PCM-Air heat exchanger air flow, saving energy and reducing noise. The selected shape is shown in Figure 38; this is the optimum shape in terms of increase in volume change, pressure drop and heat transfer.

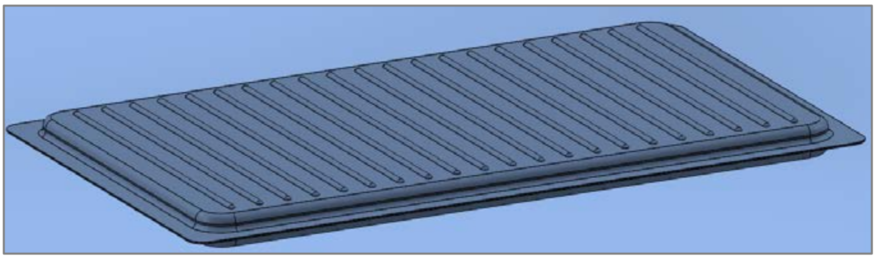

Figure 38 Optimum shape.

### *7.3.5. Conclusion*

More than 200 simulations were performed with different surface designs and air flows until the optimum design in terms of heat transfer, pressure drop and low production cost was achieved. The selected shape doubled the heat transfer and holds 13.68% more material than the existing commercial panel. Fan power is increased due to the increased pressure drop by 3 but heat transfer improvement requires lower air flow. The developed design has been fabricated and experimental tests are currently carried out to validate its performance.

### 7.3.6. References

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Santos T, Kolokotroni M, Hopper N, Yearley K. A study of panel ridges effect on heat transfer and pressure drop in a ventilation duct. Air Infiltration and Ventilation Center: Proceedings of 38th AIVC Conference, Nottingham, UK. AIVC; 2017.

## 7.4. Ventilative cooling in Norwegian schools and kindergardens

### 7.4.1. Abstract

New and refurbished buildings have to relate to ever-increasing standards regarding energy efficiency and energy consumption. This results in well insulated building envelopes with low air leakages offering reduced heating demands. However, these buildings are easily warmed up to such a degree that in order to sustain an acceptable indoor climate, removal of excess heat becomes a necessity. Through means of mechanical cooling surplus heat can be removed, or more common, the thermal climate suffers. However, to reduce energy consumption, the use of ventilative cooling solutions is settling as a solution to realize ZEBs with high standard thermal comfort.

In schools and kindergartens, the number of students per classroom and floor area is a challenge regarding removal of the heat without incurring draught. Therefore, the goal of this research has been to simulate ventilative cooling strategies to cover the cooling loads through a whole year by means of exhaust or balanced mechanical ventilation in combination with window ventilation. The conclusion is that for both types of buildings thermal comfort is possible without the need for a chiller. However, in cold climates, the risk of overcooling in shoulder seasons has to be considered in detail.

### 7.4.2. Objectives

Ventilative cooling refers to the use of ventilation air in order to reduce or eliminate the need for mechanical cooling to achieve thermal comfort. Ventilative cooling can be applied through both mechanical and natural ventilation strategies, as well as a combination of both. To achieve efficient ventilative cooling while ensuring an acceptable thermal climate, the first step is to include measures that provide minimization of heat gains.

### 7.4.3. Methodology

The methodology was to test the application of ventilative cooling solutions in cold climates through simulations of an already existing kindergarten and school in the South of Norway. The kindergarten and the schools have been analyzed by means of energy use and thermal comfort with the IDA ICE program. The validated simulation of the kindergarten has been compared to simulations of the same buildings using 1) DCV and 2) VAV (both without cooling), 3) hybrid window ventilation with exhaust fan and night set back, and 4) only window controlled natural ventilation with night set back allowed. Simultaneous and sequential strategies of the use of ventilation opening and mechanical ventilation were tested.

### 7.4.4. Results

Results show important energy savings when using ventilative cooling as an outcome of the low outdoor temperatures, the same applies for night cooling.

Simulation results indicate that solutions like hybrid ventilation could cut the annual energy consumption of energy for fans by as much as 13% for the kindergarten and 27% for the school compared to conventional mechanical ventilation. When looking at the thermal environment and indoor temperatures, it was found that for warm days it is hard to sustain acceptable temperatures without the use of night set back or mechanical cooling.

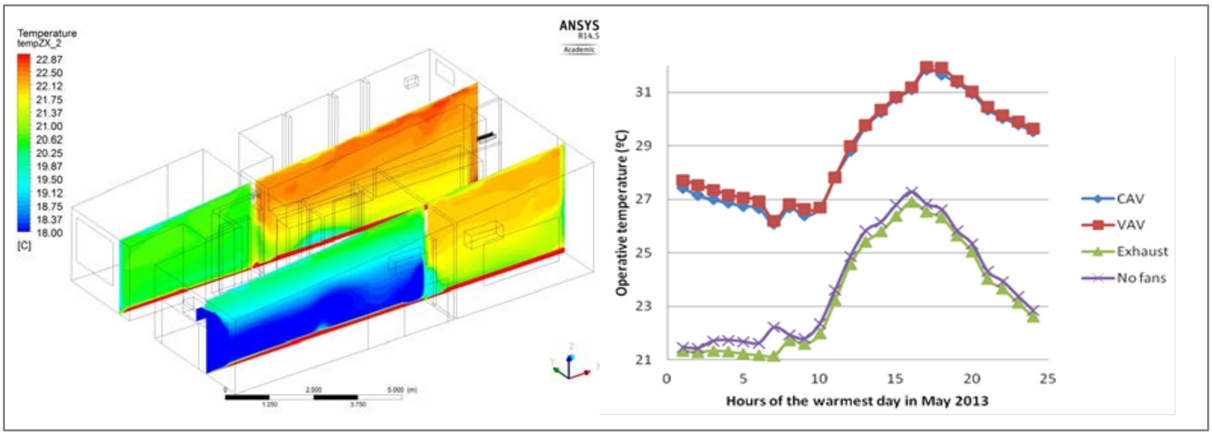


Figure 39 Detail of the cooling draught subsequent to the window opening in the school. Comparison of mechanical ventilation and exhaust (hybrid ventilation) and no fans only window opening for the warmest day in the kindergarten.

Compared to mechanical ventilation one can conclude that mixed mode ventilation is very suitable for ventilative cooling and in the simulated case, one can keep acceptable indoor temperatures even when outdoor temperatures are around 25°C.

### *7.4.5. Conclusion*

Ventilative cooling is proven relevant to highly occupied buildings. It is crucial to achieving energy targets for renovated or new zero energy buildings while maintaining the thermal comfort. However, the discomfort due to draught has to be considered, for instance by moving the ‘window row’ of students a bit away from the windows, or by controlling the opening pulse on length and degree of opening.

### *7.4.6. References*

Algrøy M. Energibruk og inneklima i skoler og barnehager med "mixed-mode" ventilasjon. Master thesis. NTNU. 2014.

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# 7.5. Ventilative cooling using a slot louvre system in a low energy building retrofit application

## 7.5.1. Abstract

An increasingly popular solution for ventilation that facilitates strategies such as night cooling is the pro-vision of purpose provided ventilation openings comprised of horizontal slotted architectural louvres. Often these are employed in single sided ventilation strategies. This research project involved full scale experimental measurements of the macroscopic air change rate (ACR) for an opening utilising an architectural slotted louvre in zero2020/NBERT, Cork, Ireland. Two separate testing campaigns were completed, during summer 2013 and 2014. Measurements were recorded under normal operation and also during controlled tests to isolate the effect of the slot louvre on wind driven ventilation. The cooling potential of the system was also investigated. The slot louvre was shown to possess higher wind dominant flow when compared with a plain opening. The slot louvre ACR were 6.5% higher compared with the plain opening ACR with even greater increases when considering comparable free opening area cases specifically. When using the optimum configuration of ventilation openings the system was unable to meet the cooling requirements for 226 hours of the year, mainly during July and August.

## 7.5.2. Objectives

The aim of the project was to investigate what are the ventilative cooling requirements in a low energy retrofit in a North European climate, such as that in Ireland, to avoid excessive overheating. Further, can these requirements be satisfactorily met by the replacement of windows with a dedicated ventilation system utilising a slotted louvre architectural component as the primary ventilation opening, operating under the principles of single sided ventilation. The objective was to investigate the aeration potential of the integrated, multi-configuration, single sided natural ventilation system installed at the zero2020 building. Finally, investigate the ventilative cooling potential of the system in a low energy building and identify where performance can be enhanced and Identify limitations to the existing approach and suggest areas for improvement.

## 7.5.3. Methodology

The methodology was based on full-scale field studies that gathered empirical data from short term air change rate measurements for a range of parameters necessary to analyze the ventilation rate performance of the single sided slot louvre system. A single cell isolated office space was used for all measurements. A similar space in the existing building was taken as a control space. The tracer gas concentration decay method was employed to measure ACR. Internal environment and boundary conditions were also monitored during tests using a range of instrumentation. The 2013 measurement campaign considered the modification in ventilation rates compared with the pre-retrofit building, in total 38 measurements of different configurations were completed 14 in the control space. The 2014 campaign involved tests with and without the slot louvre in the retrofit space, 44 tests were completed. Finally, analysis of the component cooling potential was completed using empirical correlations from measurements and the climate potential analysis tool developed in IEA Annex 62 Subtask A.

Figure 40 Building and ventilation system configurations. Left: configuration RS.02, middle: RS.03, right: RS.04. Configurations L1, L2, P1 to P3 in the middle are variations of RS.02.

### 7.5.4. Results

Figure 40 presents the retrofit building and the ventilation configurations tested in 2013. 2014 was based on variations of a single opening of RS.02 only. Figure 41 presents ACR results for 2013 and 2014 campaigns. The retrofit system produced comparable ACR values when compared with the window opening in the existing space. However, the internal environment is substantially improved in the retrofit. When the same opening with and without the louvre is compared, depending dimensions, there is up to 53% improvement in aeration efficiency. Figure 41 shows the cooling potential of the system using a TMY3 weather file for Cork, Ireland.

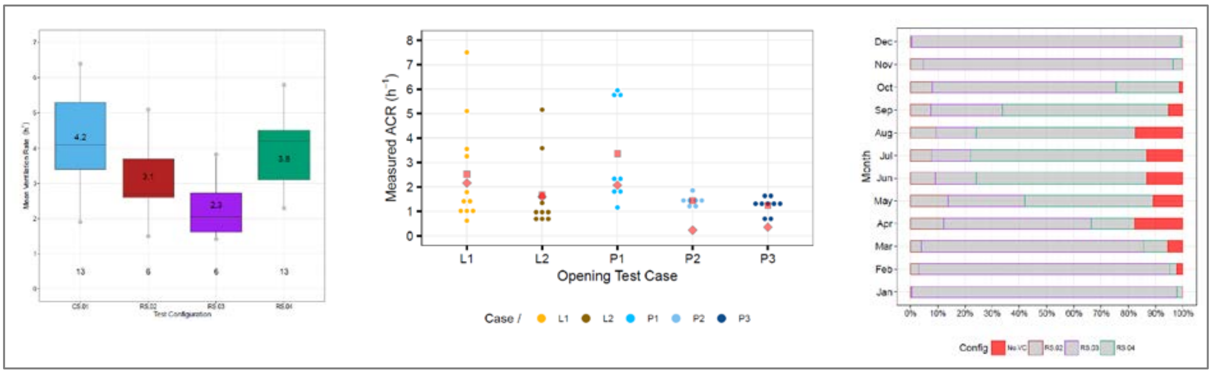


Figure 41 Building and ventilation system configurations. Left configuration RS.02, middle RS.03, right RS.04. Configurations L1, L2, P1 to P3 in Figure 2 middle are variations of RS.02.

### 7.5.5. Conclusion

The slot louvre system can provide comparable ventilation rates to window opening configurations and provides enhanced thermal performance of the building envelope. It has good cooling potential in most times of the year. However, its dimensioning requires improvement to ensure ACR values greater than 5 to provide sufficient cooling year round.

### 7.5.6. References

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# 7.6. Ventilative cooling in energy renovated single-family houses in temperate climates

## 7.6.1. Abstract

The current developments towards nearly-zero energy houses in building efficiency have increased the overheating incidents indoors. For occupants, summer thermal discomfort is an unknown challenge that they have not faced in the past. The objectives of this study are to highlight the problem of overheating in energy renovated dwellings in temperate climates and to investigate the ability of automated window opening control systems to address the risk during the peak summer period. Both dynamic and static criteria were used to carry out risk evaluation.

## 7.6.2. Objectives

The objectives of the research are to highlight and address the design challenges related to decreasing the overheating and cooling need in energy renovated dwellings, as well as, to develop a ventilative cooling concept (solution and control strategies) for this type of buildings, avoiding excessive active cooling energy use.

## 7.6.3. Methodology

The research study is based both in numerical analysis and monitoring campaign. The numerical analysis (building performance simulation tools) is conducted in 4 reference houses with high market and energy renovation potential. The analysis is focused on the Danish climatic conditions. Other temperate climatic conditions are also examined (Vienna, London and Marseille). The monitoring campaign is conducted in a fully occupied detached house from 1937, close to Copenhagen. Static and dynamic overheating and thermal discomfort metrics (7 in total) are used in a room and building level.

### 7.6.4. Results

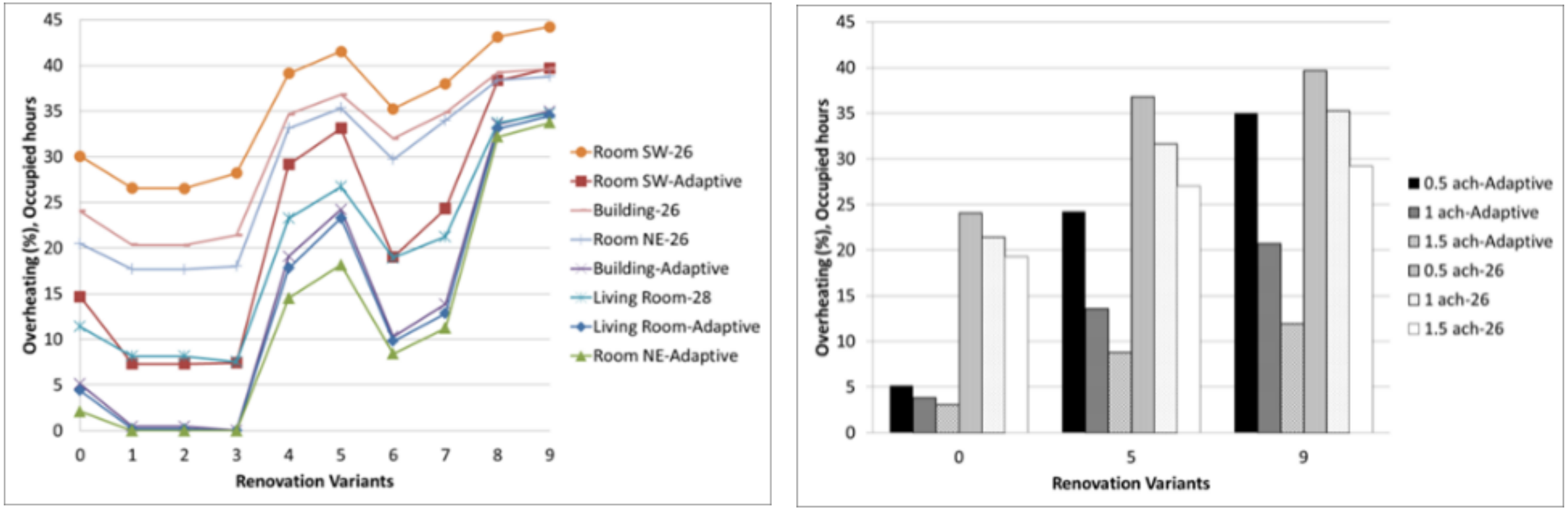


Figure 42 Overheating assessment (%) for (left) different renovation variants (right) different renovation variants and ventilation rates (S. France; room and building level; 2 metrics).

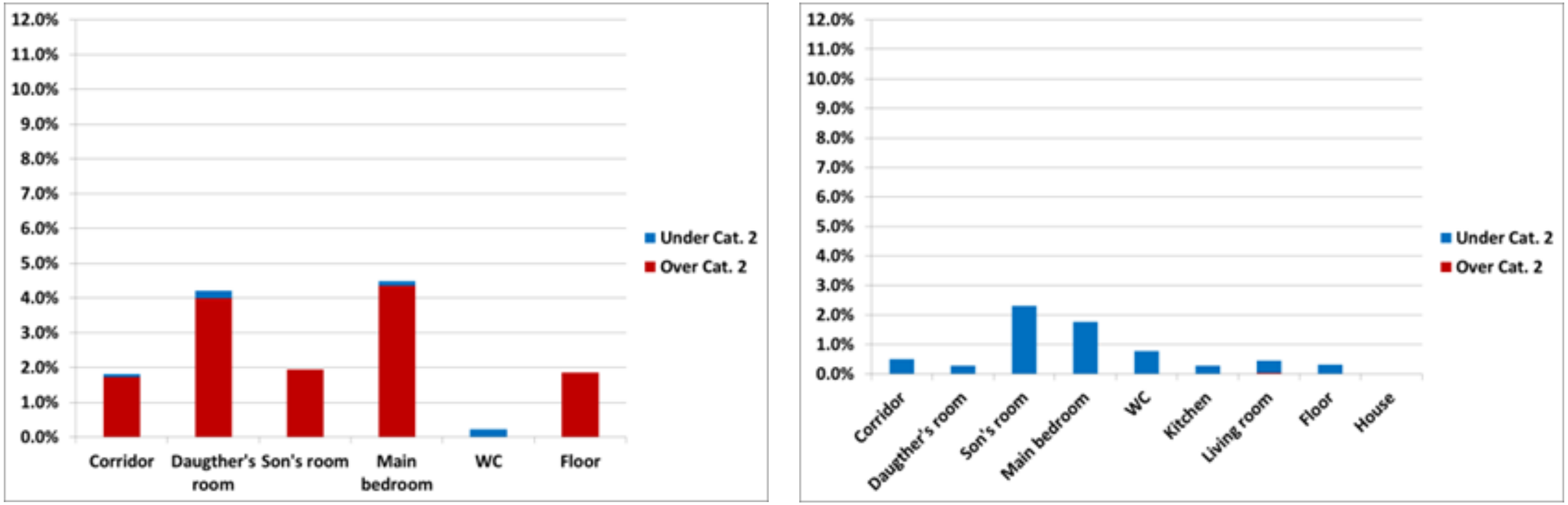


Figure 43 Thermal discomfort assessment (%) for (left) summer 2015 and manual control of windows (right) summer 2016 and automated control of roof windows (adaptive method Category II).

### 7.6.5. Conclusions

Energy renovation measures in dwellings, targeting mainly the efficiency improvement of building elements increase the average and maximum indoor temperatures, overheating risk and overheating period. Alarming measures, in terms of overheating, are the insulation of the floor and the improvement of the building airtightness. Ventilative cooling method and control strategies through window opening systems may be an attractive and energy efficient solution for dwellings in temperate conditions, only if systems are automated controlled. Manual control of window openings cannot assure indoor conditions without major violations.

The developed window opening control system is described in detail (hardware and algorithms). The window system may significantly decrease (with low energy use) the indoor thermal discomfort without any significant compromise of the air quality. The simulation of the proposed system in building performance simulation tools is possible under the proposed framework (software coupling).

### 7.6.6. References

Psomas T, Heiselberg P, Duer K, Andersen MM. Comparison and statistical analysis of long-term overheating indices applied on energy renovated dwellings in temperate climates. Indoor Built Environ 2016;0:1-13, DOI:10.1177/1420326X16683435.

Psomas T, Heiselberg P, Duer K, Bjørn E. Control strategies for ventilative cooling of overheated houses. Federation of European Heating, Ventilation and Airconditioning Associations: Proceedings of 12th REHVA World Congress, Aalborg, Denmark. Aalborg University; 2016.

Psomas T, Heiselberg P, Duer K, Bjørn E. Overheating risk barriers to energy renovations of single family houses: Multicriteria analysis and assessment. Energy Build 2016;117:138-148.

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## 7.7. Living Lab: Hybrid and natural ventilation

### 7.7.1. Abstract

The living lab is a residential building built to the Zero Emissions Building (ZEB) level. This building is in addition a test facility that has duplicated supply systems, a high level of insulation and airtightness and is highly monitored and controlled. With the goal of testing the suitability of ventilative cooling in Norway by means of use of windows opening and/or mechanical ventilation measurements and simulations in IDA ICE have been run. The main conclusions are that 1) overheating can be avoided by correct use of shading and window opening, and 2) to ensure thermal comfort the opening of windows has to be temperature difference controlled as the biggest challenge seems to be the risk of overcooling.

### 7.7.2. Objectives

The objectives of this research have been to prove the feasibility to remove heat loads from a residential building, to ensure thermal comfort and to develop a sound control system that enables this. This has been done in order to maximize the use of natural ventilation while ensuring standard rates and thermal comfort.

### 7.7.3. Methodology

The chosen methodology has been a combination of measurements to validate a simulation model in IDA ICE. Firstly measurements of temperature and air velocity in selected points of the main rooms have been realized in summer and shoulder season. For these measurements, different occupancy levels and temperature differences between indoors and outdoors have been tested. The effects of different window openings and wind velocities have been measured. Figure 44 shows the positioning and shape of the windows in all the facades of the Living Lab.

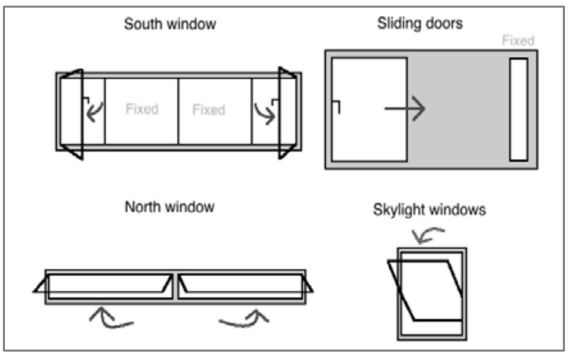


Figure 44 Left: Placing of windows in the Living Lab, Right: Window opening in the Living Lab.

Secondly, a validated model has been done in IDA ICE. This model has been used to validate and improve the control of window openings in combination with mechanical ventilation. The warmest week in Trondheim (Norway) has been used for the simulations. Preliminary simulations to determine the warmest and coldest room have been done so that these rooms are used for comparison. In addition, simulations of possible improvements of window sizing and building orientation have been done.

### *7.7.4. Results*

Measurements prove that window opening can very fast mean air velocities over comfort, and that the temperature differences between indoor and outdoor are almost linearly correlated with increasing draught rate.

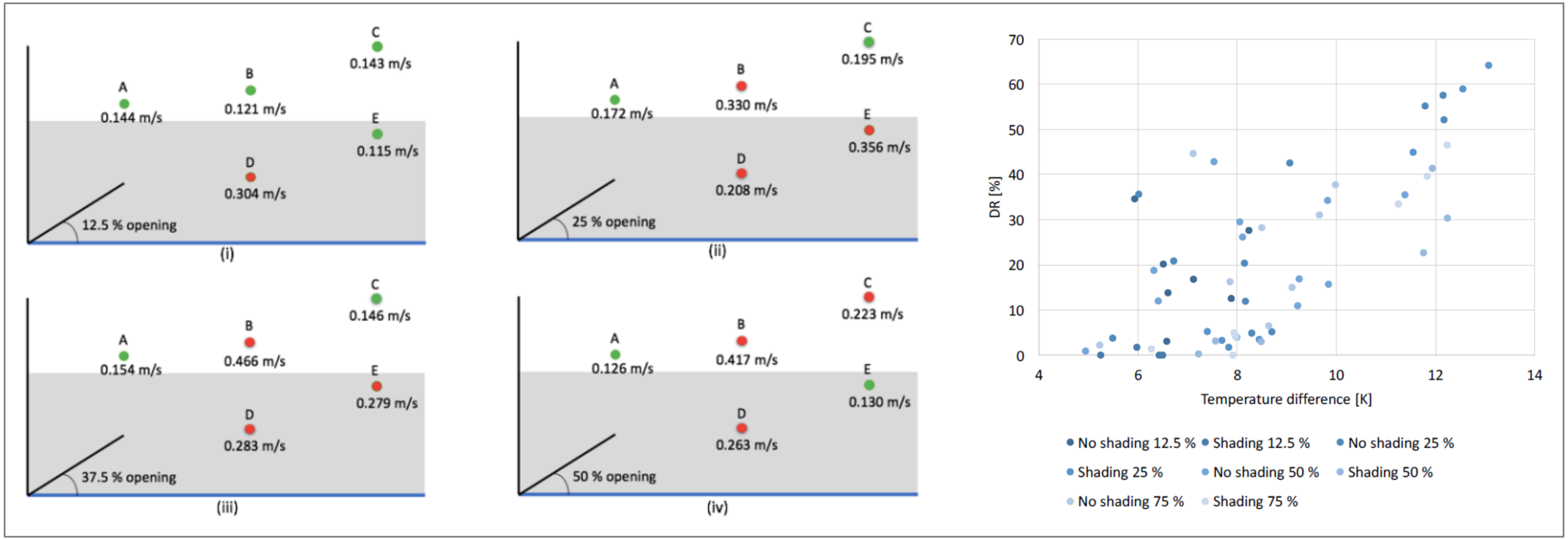


Figure 45 Air velocities at 5 cm height with i) 12.5 % window opening, ii) 25 % window opening, iii) 37.5 % window opening and iv) 50 % window opening measured by the south window. Right measured draught rate and temperature difference.

In addition, in cold climates due to the normal low temperatures, an increase of window opening may very fast incur increased heating demands by means of heating and ventilation.

For this case, the best control is proven to be the one that opens windows when the mean temperature in the house is over 24°C and gets the windows closed when the minimum temperature in the coldest room drops below 22°C.

The opening degree of the windows is also important and in this case, opening the north window in combination with the skylight windows up to 50% when the temperature differences are up to 10 degrees seem to be the most efficient cooling. However, for this case the risk of overcooling and local thermal discomfort has to be considered in combination with the wind.

### *7.7.5. Conclusion*

The use of window opening is proven efficient as a ventilative cooling mean. In the studied building, despite the high levels of insulation and high solar loads (shading was normally not used for these tests), the use of window opening and mechanical balanced ventilation removes efficiently the heat loads. However, the main constrain in this building is the local thermal discomfort that needs to be highly considered in order to ensure satisfied users. Such control needs to account for wind velocity and angle, and temperature differences between indoors and outdoors.

### *7.7.6. References*


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Risnes A. Indoor environment in ZEB living lab. Master thesis. NTNU. 2016.

## 7.8. Ventilative cooling and energy use in frozen food supermarkets

### 7.8.1. Abstract

A computation model of frozen food supermarkets within EnergyPlus was developed and validated using environmental conditions and energy data from two supermarkets. The model can be used to identify opportunities for energy reductions by ventilative cooling strategies considering the supermarket as a whole system.

### 7.8.2. Objectives

The objective of this study was to create a validated computational model of frozen food supermarkets taking into consideration both building (envelope, HVAC and lighting) and refrigeration systems and their interdependence.

### 7.8.3. Methodology

The investigation includes in-situ monitoring of energy use and environmental conditions in two frozen food stores with different HVAC but same refrigeration systems and store operation schedules. A dynamic thermal model was developed using EnergyPlus and validated using the monitored data. The model takes into account interlinked heat exchanges between building, HVAC and refrigeration systems and was used to investigate energy efficiency improvements. Two HVAC systems were examined; coupling heating, air-conditioning and ventilation (coupled system) and separating heating and air-conditioning from ventilation (decoupled system). A parametric study of night ventilative cooling is carried out and optimisation strategies are modelled.

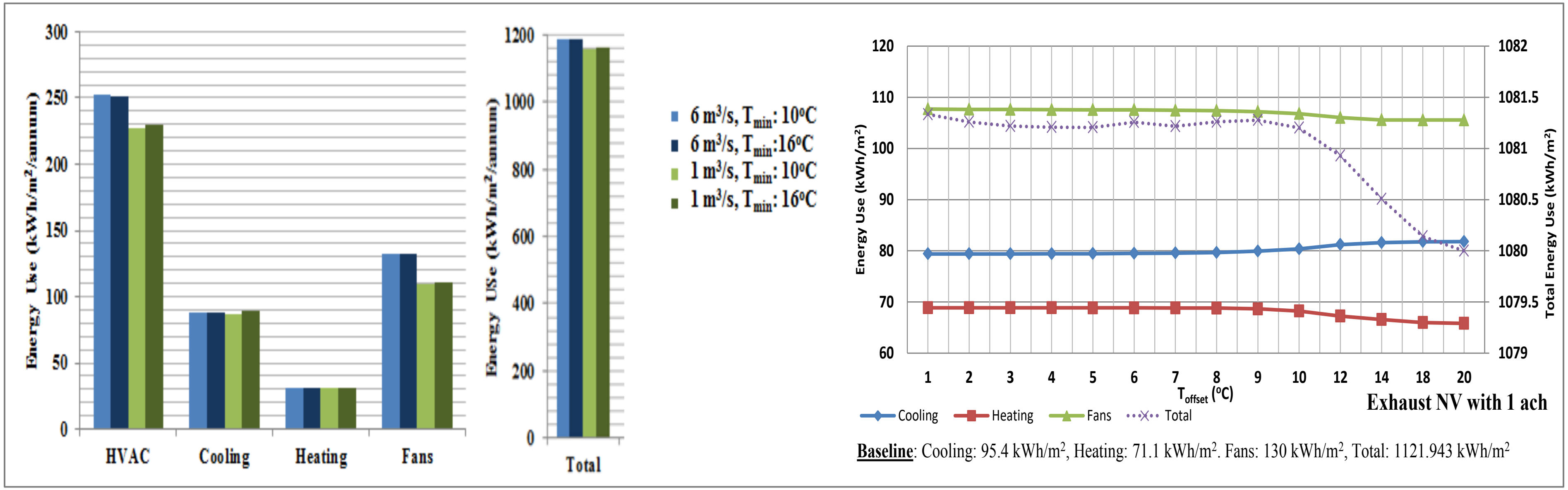


Figure 46 Left: Total annual energy use and sub-systems energy use for different air flow rates and Tmin, coupled HVAC, Right: Cooling, heating, and fans energy use for different T ofsset for Tmin=10ºC, decoupled HVAC.

### 7.8.1. Results

Analysis of the monitored data has shown that sales area temperature is highly affected by HVAC controls, refrigeration equipment and transient customers' pattern. Results indicate that refrigeration and HVAC systems are the next most energy intensive systems. Energy efficiency can be improved for both coupled and decoupled HVAC systems by incorporating night ventilative cooling and operating refrigeration cabinets with lower ambient temperature. The parametric analysis indicates that the air flow rate of night ventilation and climatic conditions are significantly correlated with the impact of night ventilation on the total energy consumption. Lower air flow rates lead to bigger energy savings along with reduced temperature setpoints inside the stores. Optimum savings were predicted if the air inside the store has 5-7 K difference with outside air. With higher temperature difference the cooling energy increases and consequently the total energy use. The higher the air flow rate, the higher this difference should be for improved changes. Night ventilative cooling results in lower cooling energy use for both HVAC systems and can lead to a reduction of up to 3.6% in total energy use which equates to 40 kWh/m$^2$/annum and is due to HVAC energy use recution (14%).

### 7.8.2. Conclusion

Night ventilative cooling has good potential for food retail stores which include high refrigeration loads. Control strategy for the application of night ventilative cooling plays an important role as it maximises energy savings without affecting the energy performance of the refrigeration equipment. As a result, cooling demand during the day is decreased and refrigeration system energy use reduced. Although this technique has good potential for total energy savings in supermarkets, condensation problems might arise on the glass surface of refrigeration equipment and care should be taken in the selection of the control parameters.

### 7.8.3. References

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# 7.9. Thermal comfort modeling and simulation in naturally ventilated low energy retrofits

## 7.9.1. Abstract

There is a significant need to retrofit existing buildings to an increasing high energy standard. However, guaranteeing annualised thermal comfort in low energy buildings can be a challenge without adequate design. While fabric and infiltration losses in a building become less significant with an attempt to make buildings passive, internal and solar gains become and overheating issue. Accurate calibrated whole building simulation models could aid in reducing the risk of overcooling and overheating in the design phase. The research project involves the modelling and simulation of thermal comfort in a low energy retrofit test-bed NBERT/zero2020 building in Cork, Ireland. The project initially involved a field study investigating a slot lourve natural ventilation system in 2015. Simultaneously long-term internal environmental data was gathered from 2013-2016 for the purpose of the second phase of the project which involves the calibration of a whole building energy and comfort modelling TRNSYS. The thermal comfort study results indicated that the use of smaller openings provided a better mean thermal sensation than the use of a larger opening in response to an overheating scenario. Smaller louvre openings were found to achieve a sufficient level of subjective comfort in 30 minutes given a daily mean external temperature of 12°C. The investigation of existing models found that the effective temperature model was the most accurate given the conditions of the field study.

## 7.9.2. Objectives

The main aim of the project was to develop a scalable calibrated model for the simulation of optimal comfort scenarios in naturally ventilated buildings. The project looks specifically at retrofits given the large need to manage our existing building stock in Ireland and in a more global sense for a European perspective. The initial stage was to consider multiple existing comfort models in a field study assessing the capability of ventilation configurations at resolving overheating. With an idea of the more appropriate models in mind a whole building simulation model is then to be calibrated considering comfort parameters such temperature and relative humidity. The overall objective is to simulate optimal comfort scenarios for low energy buildings with this calibrated tool.

## 7.9.3. Methodology

The field study methodology was one that considered all existing standards on thermal comfort. It considered both subjective and objective assessments for thermal comfort in a given control space. Figure 47 indicates the configurations investigated during the field study. Smaller louvre openings (RS.02 and RS.03) had a percentage of opening area to floor area ratio (POF) of 1.2% while RS.04 had a POF of 2.2%. The field study also involved the gathering of questionnaires that were designing in accordance with ISO 10551 for the purposes of comparing the mean thermal sensation of study participants (n = 35) with existing thermal comfort models.

Figure 47 Building and ventilation system configurations. Configurations from left to right: RS.01, RS.02, RS.03, RS.04.

### 7.9.4. Results

Figure 48 found that configurations with a POF of 1.1% (RS.02 and RS.03) showed better comfort performance than those with a POF of 2.2% (RS.04). There was also a difference seen between the height of the openings used but was not statistically significant. Negative temperature ramps observed during the study were larger than previously reported ramps. When comparing thermal comfort indices it was found that the effective temperature index outperformed the more commonly used operative temperature index. Overheating was reasonably resolved to comfortable conditions in a 30 minute period using smaller opening areas with a POF of 1.1%.

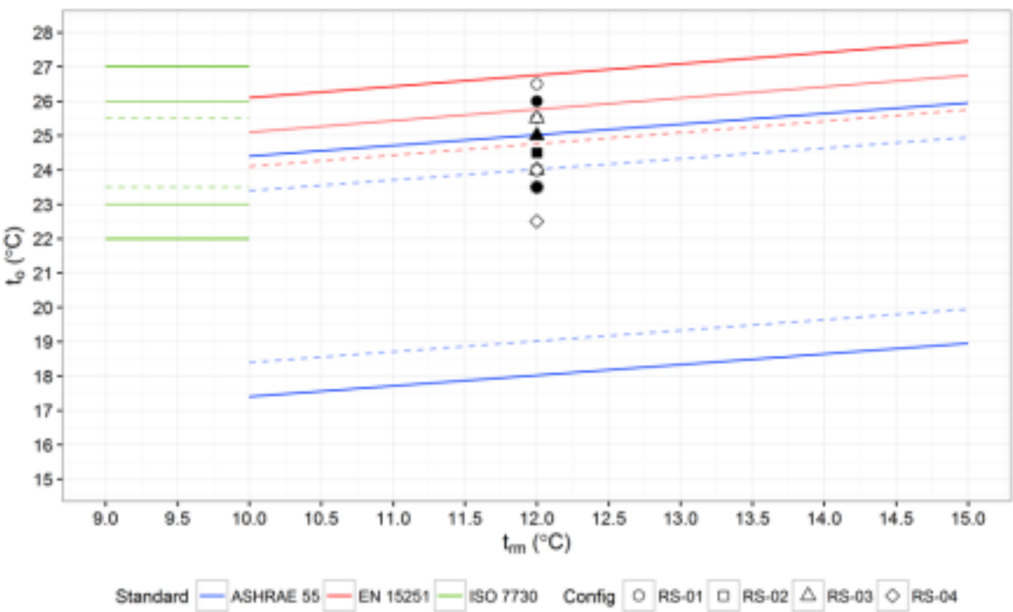


Figure 48 Results from field study. Performance with respect to standards

### 7.9.5. Conclusions

Using high-level openings with a POF of 1.1% can achieve reasonable comfort performance following an overheating scenario in 30 minutes. Consideration should be given to both humidity and temperature based models with linking thermal comfort to mean thermal sensation. There is a potential risk of overcooling with larger openings given daily mean external temperatures of around 12°C.

### 7.9.6. References

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# 7.10. Ventilative cooling on the test bench: Learnings and conclusions from practical design and performance evaluation of two Austrian buildings using ventilative cooling in urban surroundings

## 7.10.1. Abstract

Two buildings have then been chosen for detailed investigation over the course of several days during a hot summer period in 2016. Using temperature loggers and a hot wire anemometer the actual cooling performance and energy efficiency ratio (EER) equivalent of the implemented ventilative cooling system have been evaluated.

## 7.10.2. Objectives

As shown in many research projects ventilative cooling has high potential to reduce the risk of overheating and the demand of mechanical cooling supply in NZEBs. It is therefore of great interest to have certain performance indicators, like the effective cooling load [kWh/m²a], for comparison and projecting of ventilative cooling systems at hand. Ventilative cooling systems in both residential and office buidlings using either mechanical or natural ventilation have been evaluated.

## 7.10.3. Methodology

Temperatures, air velocities and electrical loads of ventilators have been recorded, in order to calculate the performance indices (air volume flow, air exchange rates, EER) for the ventilative cooling systems of two different buildings.

Data loggers were used to measure the temperatures of the outside air (Ta), the incoming air (Tz), the room temperature (Ti) and the temperature of the exhaust air (Te). The measurement interval was set to 15 minutes.

With a hot wire anemometer air velocities have been measured and allowed the calculation of air exchange rates.

## 7.10.4. Results

The analysed complex consisting of two buildings and a total of 137 flats ranging from 37 to 130 m² has been completed in 2016. Its calculated heating demands are 17.1 kWh/m²a and 18.5 kWh/m²a which are met by district heating. The building structure is reinforced concrete providing the necessary building mass.

Each building is accessible by at least two separate staircases which are connected through a central corridor. This allowed the implementation of ventilative cooling using the circulation area for night ventilation.

Ventilators on the roof enhance the air flow from the air inlet top hung windows in staircase 1 through the central corridor to the exhaust openings on the roof of staircase 2. The system is operating between 22:00 and 06:00 if the temperature in the central corridor is >22°C and 2 K higher than the outside temperature.

Figure 49 Ventilative cooling components: air inlet window, air exhaust unit with ventilator on roof.

Table 4 Operating figures of ventilative cooling system.

| | Building 1 | Building 2 |
|---|---|---|
| Number of air inlet windows | 6 | 6 |
| Nominal geometric cross section per inlet | 0.8 m² | 0.8 m² |
| Air volume flow of VC | 22000 m³/h | 11000 m³/h |
| Net floor area affected by VC (corridors only) | 996 m² | 750 m² |
| Total inlet cross section area per VC affected floor area | 0.5 % | 0.6 % |
| Ceiling height | 2.6 m | 2.6 m |
| Air change rate of VC affected area | 8.5 $h^{-1}$ | 5.6 $h^{-1}$ |

Figure 50 shows the measured temperatures during the course of three consecutive nights in August 2016.

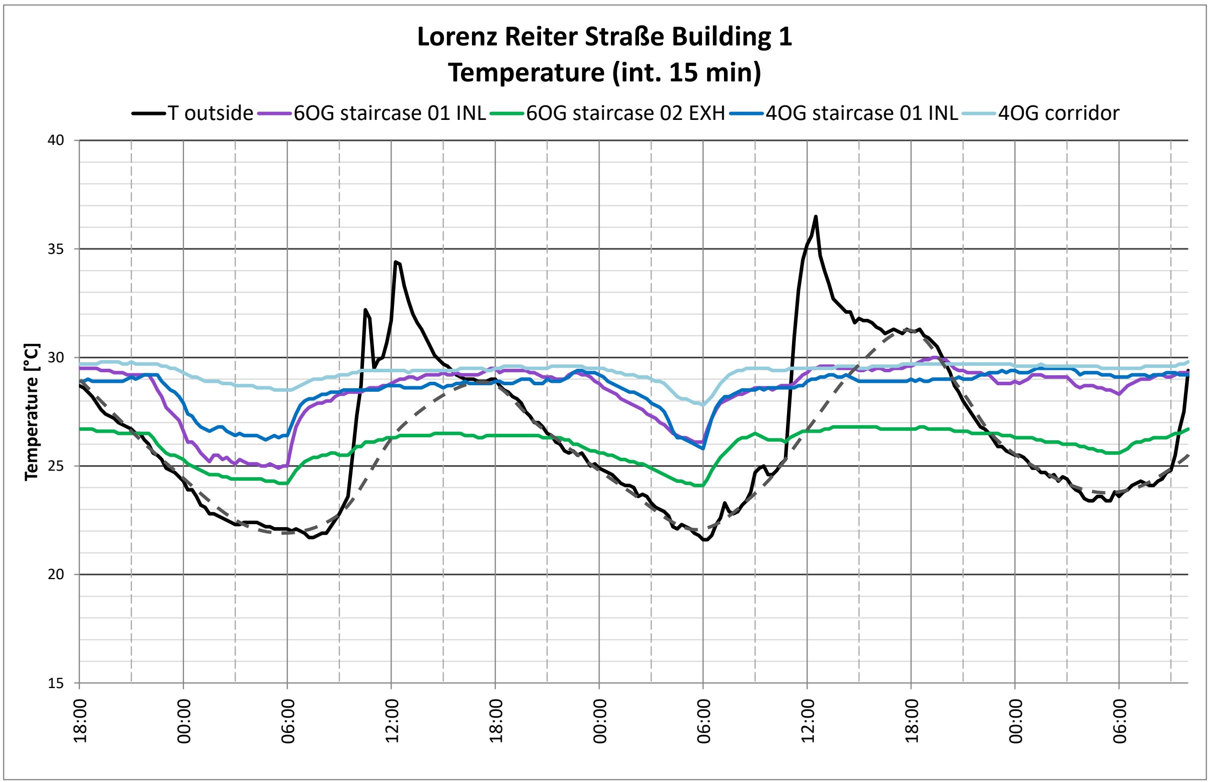



Figure 50 Diagram showing temperature curves of building 1.

Table 5 Performance figures of ventilative cooling system.

| | Building 1 | Building 2 |
|---|---|---|
| Volume flow of ventilative cooling | 22000 m³/h | 11000 m³/h |
| Electrical power drain of ventilators | 1040 W | 520 W |
| Annual operating hours | 601 h/a | 601 h/a |
| Annual discharged cooling energy | 23.2 MWh/a | 11.6 MWh/a |
| Discharged cooling energy in relation to corridor area | 23.3 kWh/m²$_{NF}$a | 15.5 kWh/m²$_{NF}$a |
| Discharged cooling energy in relation to indirect conditioned net floor area | 2.6 kWh/m²$_{NF}$a | 1.8 kWh/m²$_{NF}$a |

| | | |
|---|---|---|
| Annual electrical power consumption of ventilators including controls and windows | 974 kWh/a | 487 kWh/a |
| Seasonal energy efficiency ratio (EER) | 24 | 24 |

### 7.10.5. Conclusions

The results showed that mechanical systems reached cooling loads of 15.5 and 23.3 kWh/m² NFA and a very good energy efficiency ratio (EER). The EER showed a value of 24. Ventilators with low energy consumption, the well-chosen size of air inlets (automatic operated windows) and the low pressure drop of the on-roof ventilation ducts made this EER possible.

# 7.11. Control strategy of housing components for ventilative cooling

## 7.11.1. Abstract

To maximize the utilization of ventilative cooling, the effect of automatic cooperation between cooling devices and windows for reducing operating time of cooling devices and improvement of indoor thermal confort are verified by field measurements. The operating time was remarkably decreaced by ventilative cooling with the comfort range of PMV.

## 7.11.2. Objectives

This project is aimed at maximizing the utilization of ventilative cooling with a control system for operating cooling/heating devices and windows. The effect of the system was verified by field experiments.

## 7.11.3. Methodology

Figure 51 shows the appearance of the experimental house. Temperature and humidity of each room are measured at 1.1 m height from the floor. Other factors which are needed to calculate PMV are assumed. PMV value of each floor is updated in real time and cooling devices and windows are operated automatically to adjust the PMV value of each room from -0.5 to 0.5. Windows are opened prior to using cooling devices when external air is good for ventilative cooling. Table 6 shows the amount of heat generation from occupants, lighting, appliances and cooking.

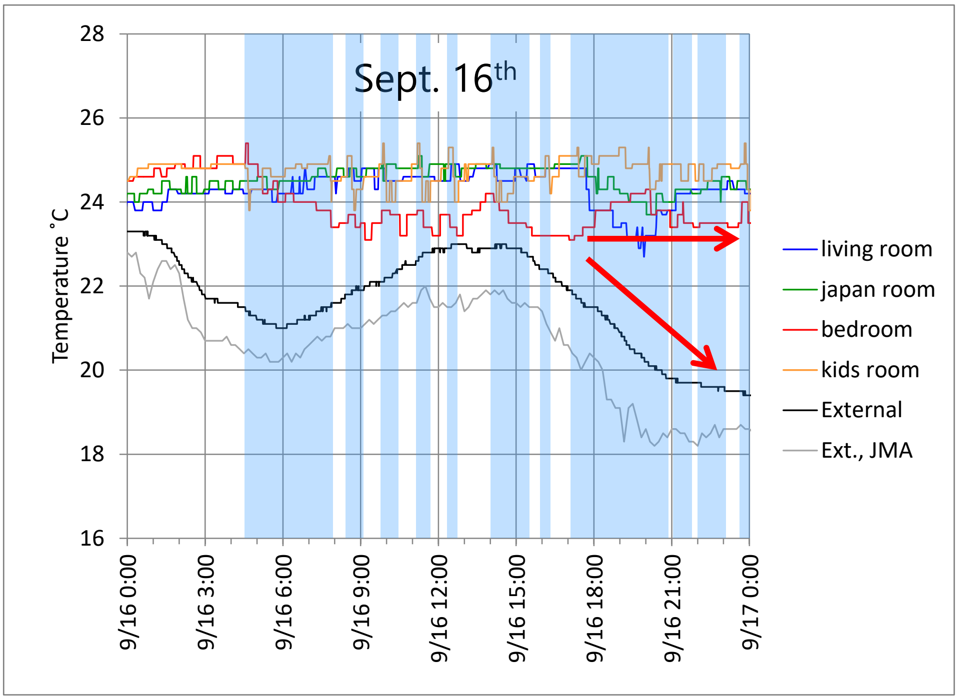
Figure 51 Experimental house.

Table 6. The amount of heat generation.

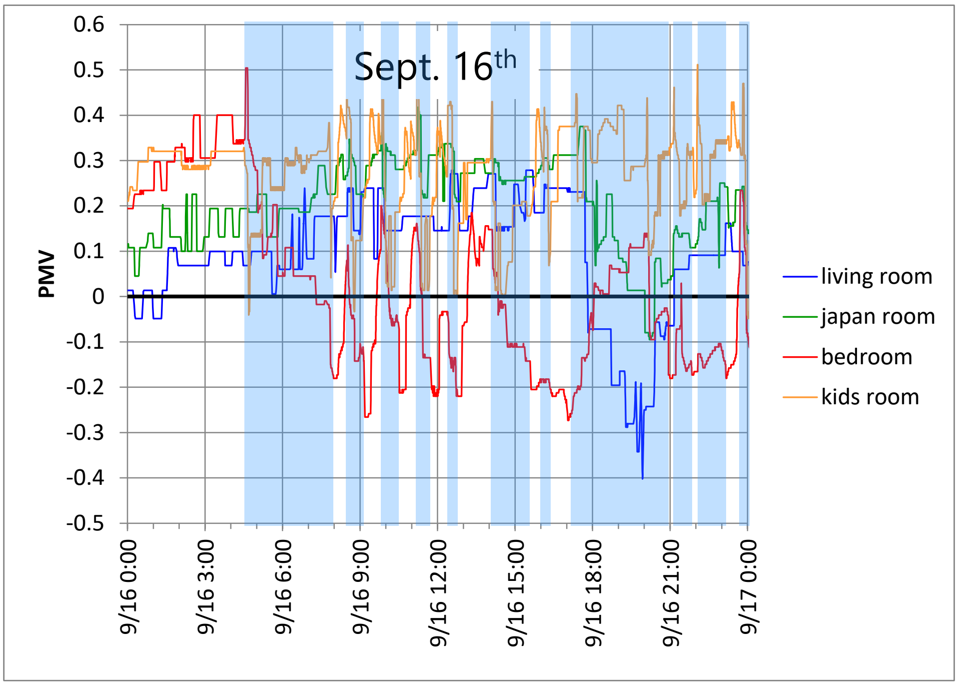
| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| L | Occupants | 0 | 0 | 0 | 0 | 0 | 0 | 90 | 270 | 90 | 90 | 90 | 90 | 90 | 90 | 0 | 0 | 270 | 270 | 270 | 270 | 180 | 180 | 90 | 0 | |
| | Lighting | 0 | 0 | 0 | 0 | 0 | 0 | 180 | 180 | 180 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 270 | 270 | 270 | 270 | 270 | 270 | 270 | 0 | |
| | Appliances | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | |
| K | Lighting | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 60 | 60 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 60 | 60 | 60 | 0 | 0 | 0 | |
| | Cooking | 0 | 0 | 0 | 0 | 0 | 0 | 540 | 0 | 0 | 0 | 0 | 0 | 270 | 0 | 0 | 0 | 0 | 540 | 540 | 0 | 0 | 0 | 0 | 0 | |
| | Refrigerator | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | |
| MBR | Occupants | 180 | 180 | 180 | 180 | 180 | 180 | 90 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 90 | 180 | |
| | Lighting | 0 | 0 | 0 | 0 | 0 | 0 | 90 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 90 | 90 | 0 | |
| CR | Occupants | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 90 | 90 | 90 | 90 | |
| | Lighting | 0 | 0 | 0 | 0 | 0 | 0 | 90 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 180 | 180 | 0 | 0 | |
| 1FHL | Lighting | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 60 | 60 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 0 | |
| UT | Lighting | 0 | 0 | 0 | 0 | 0 | 0 | 40 | 40 | 40 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 40 | 40 | 40 | 40 | 40 | 40 | 0 | |
| | Appliances | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 90 | 90 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 90 | 90 | 0 | |
| BATH | Lighting | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 60 | 0 | |
| 2FHL | Lighting | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 60 | 60 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 0 | |

### 7.11.4. Results

Figure 51 shows the distribution of the air temperature in each room. Air temperature of every habitable room changes between 22-26˚C in each case. It is found that room temperature on the first floor follows external temperature in the case of using ventilative cooling. It is also found that PMV value changes between -0.5 to 0.5 in both cases, this means that ventilative cooling can make the habitable rooms comfort and can remarkably decrease the operating time of mechanical cooling.




Only mechanical cooling




Mechanical cooling + Ventilative cooling

### 7.11.5. Conclusions

The effect of taking ventilative cooling was evaluated by field experiments. With ventilative cooling, moderate thermal condition can be maintained and operating time of cooling devices was remarkably decreased.

## 7.12. International ventilative cooling application database

### 7.12.1. Abstract

Within this IEA Annex 62 the joint research activity of International ventilative cooling application database has been carried out, systematically investigating the distribution of technologies and strategies within ventilative cooling. The database has been filled, based on desktop research, by IEA Annex 62 participants. The ventilative cooling database contains 91 buildings, located in Europe (i.e. Denmark, Ireland and Austria). The building-datasheets offer illustrative descriptions of buildings of different usages, sizes and locations, using ventilative cooling as a mean of indoor comfort improvement.

### 7.12.2. Objectives

Ventilative cooling covers a broad range of measures, applying ventilation flow rates to reduce the cooling loads in buildings, either by withdrawing heat from the building or by offering increased air velocities and thus increased personal convective and latent heat transfer. At first glance, ventilative cooling seems to be an easy choice. At second glance it still is an excellent choice, but forming a truly sensitive system, which interdependencies have to be studied and understood thoroughly. Interdependencies exist towards climate zone, topography, building-use, shape and size, users' comfort expectations as regards thermal and acoustic comfort as well as security levels and many other aspects. Facing this tremendous variety of parameters and options the idea of the International database was to firstly offer an illustrative collection of buildings with ventilative cooling and secondly compare the solutions applied, find typical 'patterns' and draw conclusions on both application guidelines to be published and for further R&D to be carried out.

### 7.12.3. Methodology

The database is structured as both a ticking-list-like building-spreadsheet and a collection of building-datasheets. The database defines a rigid matrix of specific building qualities for each building entry. The main topics of this matrix are:

- General building specifications: address, building category, year of construction, special qualities, location, climate;
- Ventilative cooling site design elements: solar site design and wind exposure design, evaporative effects from plants or water;
- Ventilative cooling architectural design elements: shape, morphology, envelope, construction and material;
- Ventilative cooling technical components: airflow guiding components, airflow enhancing components, passive cooling components;
- Actuators, sensors and control strategies;
- Building energy systems: heating, ventilation, cooling, electricity;

- Building ownership and facility management structures.

Since the database was meant to be filled by different researchers it was crucial to offer precise explanation of each category's exact meaning. This has been done in a specific 'building-spreadsheet manual'.

### *7.12.4. Results*

- Building use is dominantly office in (55%), educational (21%) and others (22%). Only 8% residential;
- Location is dominantly urban (60%);
- Ventilative cooling site design elements are applied in 65%, quite equally distributed between solar site design, wind exposure design and evaporative effects;
- Ventilative cooling architectural design elements are applied in 95%, dominantly by morphology, envelope and construction-material (66% to 78%), less by form (49%);
- Airflow guiding ventilation components are used widely in 99% of the buildings, dominantly by windows, rooflights, doors (96%), significantly more seldom by dampers, flaps, louvres (44%) or by special effect vents (5%);
- Airflow enhancing ventilation components are applied in 66%, fully dominated by atria (63%), with some chimneys (16%) and only very rare cases of others;
- Passive cooling components are used in 26%, dominantly by convective cooling components (22%), with only very rare cases of others;
- Actuators are identified in 66%, dominated by chain actuators (57%), followed by linear actuators (9%);
- Sensors are identified in 88%, including the frequent use of temperature, humidity, $CO_2$, wind, rain and solar radiation;
- Control strategy is reported as hybrid in 58%, as automatic in 29%, as manual only in 4%.

### *7.12.5. Conculsions*

The IEA Annex 62 joint research project of International ventilative cooling database illustrates that this method is used not only in traditional, pre-air-condition architecture, but also in temporary European and international low energy and net zero energy buildings. Still it is a technology far from being widespread employed.

### *7.12.6. References*

Holzer P, Psomas T, O'Sullivan P. International ventilation cooling application database. Federation of European Heating, Ventilation and Air conditioning Associations: Proceedings of 12th REHVA World Congress, Aalborg, Denmark. Aalborg University; 2016.

http://venticool.eu/annex-62-publications/deliverables/ (30/10/2017)

# 8. Glossary of ventilative cooling simulation tools

## 8.1. Introduction

During the last decade, simulation tools have become an integral part of the design process. Building performance simulation tools (BPST) are commonly applied to predict indoor climate and energy use of miscellaneous HVAC and building physics related concepts in buildings. Rule of thumbs can and are applied but they are limited to well-known and established situations and to smaller scale buildings without multi-zone air flow. In all the rest of the cases, engineers and architects are seeking for assurance in their decision-making processes. This support can be provided by building performance simulation tools (BPSTs), but not without any risks. The accuracy and reliability are very important parameters and several IEA EBC tasks were focused on assessing these parameters. Task 12 has created a number of procedures for testing and validating building simulation software, task 22 contributed to assess accuracy of BPS to predict solar and low-energy concepts, task 30 investigated why BPSTs are not widely used in design process, task 34 evaluated accuracy and capability of analysis and tools algorithms and developed BESTEST procedure. Designers wish the natural ventilation to be combined with HVAC systems. Moreover, analysis of outdoor air systems and natural ventilation should be improved in the future development of BPST to be able to simulate complex and detailed building components.

Simulation tool developers seldom state together both the capabilities and limitations of their tools. The aim of this chapter is to present a list of software abilities to simulate ventilative cooling. The focus of this chapter is not to validate software as it was in the previous tasks, although it is taken under consideration if tools are validated, but to give an overview of tool features, ventilative cooling strategies and required input parameters, ability to simulate performance of ventilative cooling components, other parameters that interplay with performance of ventilative cooling and ventilative cooling control with regards to specific parameter. These contributors are advanced users and/or software developers.

The subject of this chapter is to address a broad audience, including architects, consulting engineers, software developers and simply all those who are working with ventilative cooling concept both by integrating it in the building design process or by improving BPSTs. To support that objective, each of the evaluated tools is not only summarized in matrix manner but also shortly described indicating key andvantages and disadvantages, real every day-use experience with the tool, recommendations for which design stage it is most beneficially used, if multi-zone model works for each configuration, what user should be mostly aware of when choosing one tool or another.

## 8.2. Tool matrix comparison

| | | Dial + | BSim | TRNSYS + TRNFLOW | Energy Plus |
|---|---|---|---|---|---|
| 1. General characteristics of the software | General characteristics of the software | | | | |
| | Monozone or multizone calculation | Monozone | Monozone/Multizone | Multizone | Multizone |
| | Initial handling of the software | Really easy, the user follows the interface step by step with the help of pictures and predefined materials and profiles (ventilation, internal gains and others) | Relatively easy. Interface constructed in tree structure with building components and systems. On the same interface is visible drawing (geometry) of the room/building | Steep learning curve | Steep learning curve |
| | Level of expertise of the user (researcher, consultant engineer, architect, practitioner) | Researcher, consultant engineer, architect, practitioner | Researcher, consultant, architect | Retail version-medium level user (engineer). Possibility for third party component development - programmer, researcher level expected | Researcher, consultant engineer |
| | Flexibility of the input parameters | To some extent | To some extent | High flexibility | High flexibility |

| | | | | | |
|---|---|---|---|---|---|
| | Transparency of the input parameters (reports, indicators, visualization, tricky interface, implicit or hidden hypothesis) | Good | Acceptable | High degree of detail (intuitive and easy interface, clear hypothesis) | Hypothesis are explicitly described in the I/O reference guide; no reports, indicators, visualization available |
| | Quality of graphs, reports, data exporting, interpretation of results | Good | Could be improved | Graphical reports can be generated during the simulation with limited customization, but it allows to export the data with a raised degree of resolution | Outputs are printed on csv files or sql format; results elaboration and interpretation of results, as well as graph preparation is in responsibility of the users |
| | Complexity of the possible cases | Simplification applied to a room only | Model complexity should be developed gradually. Simplifications help to avoid errors | High complexity of the possible cases | - |
| | Calculation time | Depends on number of time steps. Simple models solved under 20 seconds, more complex models solved within couple of minutes | Depends on number of time steps and building construction material. Simple models solved under 1 minute, more complex models solved within couple of minutes | Simple models are solved in seconds, calculation time depends on the complexity of the model created | Depends on number of time steps. Simple models solved under 20 seconds, more complex models solved within a dozen of minutes |
| | Bugs | Occasionally | Can occur | Limited, a mailing list is available for bugs and issues | The software is constantly being updated |

| | | | | | |
|---|---|---|---|---|---|
| | Assistance, user manual, language availability | Good user manual in French, interface in German, Italian, English | Poor support, not updated user manual. User manual available in Danish and in English | TRNSYS manual provides a step by step guide to use it,<br>TRNSYS is available only in English | Very detailed I/O reference guide and engineering guide in English; efficient helpdesk and support group; good training material provided. Bigladder co. |
| | Price/educational price | 1490 euros | Price depends on many criteria[26] | Price depends on several criteria. TRNFLOW needs to run on TRNSYS 18 or previous. Current price for TRNFLOW is in the rangeof 1900 -2500 Euros27 | Open source software, distributed under the terms of a permissive, BSD-style license |
| | Accuracy of the software | | | | |
| | Is the software thermal model validated according to EN ISO 15255 or equivalent for a mechanically ventilated and cooled scenario (internal temperature deviation <0.5°C, | Yes, class 3-A | Yes | No | ANSI/ASHRAE Standard 140-2011<br>IEA SHC Task 34/Annex 43 (BESTest) |

[26] http://www.sbi.dk/indeklima/simulering/bsim-building-simulation/copy_of_bestilling-og-priser/bestilling-og-priser (30/10/2017)
[27] http://www.trnsys.com/order/ (30/10/2017)

| | | | | | |
|---|---|---|---|---|---|
| | maximum cooling power <5%, 24h mean power <5%, mention classification category and class) | | | | |
| | Is the software thermal model validated according to EN ISO 15265 or equivalent for heating and cooling needs (deviation class A<5%, class B<10%, class C<15%) | Yes, class B | - | No | ANSI/ASHRAE Standard 140-2011<br>IEA SHC Task 34/Annex 43 (BESTest) |
| | Is the software thermal model validated according to EN ISO 13791 or equivalent for internal air temperature for a free running room (max mean and min temperature deviation < 0.5°C) | Yes | - | Not according to EN ISO 13791.The same heat balance method (algorithm) as Energy Plus | ANSI/ASHRAE Standard 140-2011<br>IEA SHC Task 34/Annex 43 (BESTest) |

| | | | | | |
|---|---|---|---|---|---|
| | Does the software calculates correctly natural ventilation | (Yes) for stack ventilation | (Yes) | TRNSYS is compliant with the ANSI/ASHRAE Standard 140-2001: ‘Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs’. TRNFLOW is the integration of the multizone air flow model COMIS (Conjunction of Multizone Infiltration Specialists) into the thermal building module of TRNSYS (Type 56). COMIS has been developed in an international collaboration in the frame of the IEA Annex 23 | The EnergyPlus airflow network model was validated by comparing model results with a large set of high-quality laboratory measurements from ORNL and using measured data obtained from the Building Science Lab (BSL) at FSEC. Zhai J. et al. performed airflow models evaluations by comparing predicted airflow from EnergyPlus, CONTAM and ESP-r airflow network models with measured airflow in laboratory experiments across 8 defined scenarios at steady conditions [1]. They concluded that all the models yielded similar airflow predictions, which are within 30% error for the simple cases evaluated. The worst results were obtained for buoyancy driven single-sided, wind driven cross ventilation and combined buoyancy and wind driven |

| | | | | | |
|---|---|---|---|---|---|
| | | | | | natural ventilation configuration, whereas buoyancy driven cross ventilation error is less than 10%. It is well known that airflow network models cannot generally well represent single-sided ventilation, as it is mainly driven by turbulent fluctuations of wind pressures, neglected in nodal models |
| 2. Outputs linked to ventilative cooling | Outputs from ventilative cooling comfort indicators | | | | |
| | Number hours or % of time over/under adaptive comfort (EN ISO 15251:2007) | Yes | No | Yes | Yes |
| | Number of hours or % of | Yes | Yes | Yes | not explicitly, by data post- |

| | | | | | |
|---|---|---|---|---|---|
| | time above/under fixed temperature | | | | processing |
| | Number of hours or % of time over 10% PPD curve | No | No | Yes | not explicitly, by data post-processing |
| | Other indicators | | | Number of hours over/under adaptive comfort zones (ASHRAE 55). Predicted mean vote (EN ISO 7730:1995). It is possible to implement any other indicator through the use of a 'line of command' indicator | Zone Thermal Comfort Mean Radiant Temperature<br>Zone Thermal Comfort Operative Temperature<br>Zone Thermal Comfort Fanger Model PMV<br>Zone Thermal Comfort Fanger Model PPD<br>Zone Thermal Comfort Clothing Surface Temperature<br>Zone Thermal Comfort Pierce Model Effective Temperature PMV<br>Zone Thermal Comfort Pierce Model Standard Effective Temperature PMV<br>Zone Thermal Comfort Pierce Model Discomfort Index<br>Zone Thermal Comfort Pierce Model Thermal Sensation Index<br>Zone Thermal Comfort KSU Model Thermal Sensation Index |

| | | | | | |
|---|---|---|---|---|---|
| | | | | | Zone Thermal Comfort ASHRAE 55 Adaptive Model 80% Acceptability Status<br>Zone Thermal Comfort ASHRAE 55 Adaptive Model 90% Acceptability Status<br>Zone Thermal Comfort ASHRAE 55 Adaptive Model Running Average Outdoor Air Temperature<br>Zone Thermal Comfort ASHRAE 55 Adaptive Model Temperature<br>Zone Thermal Comfort CEN 15251 Adaptive Model Category I Status<br>Zone Thermal Comfort CEN 15251 Adaptive Model Category II Status<br>Zone Thermal Comfort CEN 15251 Adaptive Model Category III Status<br>Zone Thermal Comfort CEN 15251 Adaptive Model Running Average Outdoor Air Temperature<br>Zone Thermal Comfort CEN 15251 Adaptive Model Temperature |
| | Graphical indicators (carpet plots, cake plots, | Column or line graphs of all calculated parameters | Column or line graphs of all calculated parameters | Limited dynamic graphical outputs capabilities | No graphical outputs |

| | | | | | |
|---|---|---|---|---|---|
| | others) | | | | |
| | **Outputs from ventilative cooling energy indicators** | | | | |
| | Cooling need with/without free cooling (prEN 15265:2007) | Yes | Yes (without free cooling) | Yes. Not according to this standard | Yes |
| | EER | No | No | Yes | Yes |
| | COP | No | No | Yes | Yes |
| | SFP for mechanical ventilation | No | No | - | Yes |
| | SEC | No | No | Yes | Yes |
| | Cooling power (prEN15255:2007) | Yes | Yes | Yes. Not according to this standard | Yes |
| | Hours of use of cooling machine | Can be derived after data exporting to i.e. Excel | Can be derived after data exporting to i.e. Excel | Yes | Can be derived from data exporting |
| | Primary energy for fans | Can be derived after data exporting to i.e. Excel | Can be derived after data exporting to i.e. Excel | Yes | Yes |
| | Primary energy for cooling | Can be derived after data exporting to i.e. Excel | Can be derived after data exporting to i.e. Excel | Yes | Yes |
| | Cooling peak power | Yes | Yes | Yes | Yes |
| | Risk of excessive energy use due to misuse (i.e. blinds, low internal set point, high air flow) | No | No | No | No |

| | | | | | |
|---|---|---|---|---|---|
| | Ventilative strategies implemented in the software | | | | |
| | Natural ventilation | | | | |
| | Differentiation of natural ventilation to occupied not occupied hours | Yes | Yes | Yes | Yes |
| | Differentiation of natural ventilation based on inside-outside air ΔT | Yes | No | Yes | Yes |
| | Combination of mechanical and natural ventilation | Yes | Yes | Yes | Yes |
| 3. Ventilative cooling strategies and input parameters | Differentiation between automatic and manual | - | - | Yes | - |
| | Possibility to define advanced control (weather compensation, multiple set points) | No | Multiple set point | Yes | Yes |
| | Possibility to take into account multiple windows at different stack heights | Yes | Yes | Yes | Yes |
| | Single sided ventilation | Yes | Yes | Yes | Yes (even though results are not as accurate as cross or buoyancy driven ventilation) |
| | Cross ventilation | No | Yes | Yes | Yes |

| | | | | | |
|---|---|---|---|---|---|
| | Stack (more levels) | No | Yes | Yes | Yes (if thermal zoning is properly done) |
| | Mechanical ventilation | | | | |
| | CAV | Yes | Yes | Yes | Yes |
| | VAV | Yes | Yes | Yes | Yes |
| | Night cooling | Yes | Yes | Yes | Yes |
| | Zone control ventilation | No | Yes | Yes | Yes |
| | Inlet control ventilation | No | Yes | Yes | Yes |
| | Ventilative components implemented in the software | | | | |
| | Ceiling fans | No | No | No | No |
| | Buried pipes | No | No | Yes | Yes |
| | Evaporative cooling (indirect or direct) | No | No | Direct evaporative cooling | Yes |
| | Venturi and powerless rotating exhaust ventilators | No | No | No | No |
| | Wind catchers and wind scoops | No | No | No | Not explicitly, special knowledge is required to develop model |
| | Double facade | No | Special knowledge is required to develop model | Yes | Not explicitly, special knowledge is required to develop model |

| | | | | | |
|---|---|---|---|---|---|
| | Ventilated wall | No | No | Yes | Yes |
| | Swamp cooler | No | No | Yes | Yes |
| | Exhaust fans | No | Yes | Yes | Yes |
| | Trickle vents | No | No | Yes | No |
| | PCM cooling and ventilation systems | No | No | Yes, through third party components | No |
| | **Other parameters taken into account** | | | | |
| | Coupled natural ventilation and air temperature | Yes | Yes | Yes | Yes |
| | Thermal mass | Yes | Yes | Yes | Yes |
| | Surface resistance to thermal mass | Yes | Yes | Yes | Yes |
| | Dynamic solar protection calculation and control | Yes | Yes | Yes | Yes |
| | Wind influence | No | Yes | Yes | Yes |
| | Hourly ventilation strategies | No | Yes | Hourly or sub-hourly | Yes |
| | Combined mechanical and natural ventilation | Yes | Yes | Yes | Yes |
| | Opening geometry (form, position) | Only rectangle | Yes | Yes | Yes |
| | Obstacles to openings (grids, nets, multiple | Definition with opening ratio | Yes with regards to solar shading. No with regards | Yes | Definition with discharge coefficient |

| | | | | | |
|---|---|---|---|---|---|
| | opening passages) | | to air flow | | |
| | Preheating of incoming air from blinds or façade typology | No | No | Yes | No |
| | Can ventilative cooling strategy be controlled with regards to below listed parameters? | | | | |
| | Air temperature in the room | Yes | After modification operative temperature can be approximated to air temperature | Yes | Yes |
| | Operative temperature in the room | No | Yes | Yes | Yes |
| | Outdoor temperature | Yes | Only night cooling | Yes | Yes |
| | $CO_2$ | No | Yes | Yes | Yes, special knowledge required to set the Energy Management System |
| | Relative humidity | No | Yes | Yes | Yes, special knowledge required to set the Energy Management System |
| | Absolute humidity | No | Yes | Yes | Yes, special knowledge required to set the Energy Management System |
| | - Maximum wind speed | No | No | Yes | Yes |

| | | Dial + | Bsim | TRNSYS | Energy Plus |
|---|---|---|---|---|---|
| 4. Other issues | $CO_2$ concentration calculation | - | - | Yes | No |
| | Occupant control: opening and closing probability values | - | - | Yes, through third party components or calculators | Yes |
| | Modulation of venting area according to inside-outside temperature difference | - | - | Yes | Yes |
| | | | | | |

## 8.3. Summary of examined software

### *8.3.1. Dial+*

DIAL+[28] is a continuation of the DIAL-Europe project financed by the European commission. This software suite includes two modules DIAL+Lighting for daylighting and electric lighting and DIAL+Cooling for thermal and natural ventilation simulations.

Ventilative cooling is taken into account through monozone natural and mechanical ventilation models simulated at an hourly time step. The natural ventilation model develops single sided ventilation strategy based on stack effect. The influence of the wind is not taken into account.

There are different natural ventilation modes available in the software:

- Windows are closed;
- Manual during occupancy (window open when $T_{in}$>26°C during working hours);
- Automatic during occupancy (window open when $T_{out}$<$T_{in}$ and $T_{in}$>21°C during working hours);
- Automatic 24/24h (window open when $T_{out}$<$T_{in}$ and $T_{in}$>21°C 24/24h).

The geometry of the window is considered (width and height) with its opening ratio. Specific opening possibilities are available including roof windows.

Mechanical ventilation can also be used as ventilative cooling strategy as an increased airflow rate, when the external conditions are favourable. The modulation of the mechanical ventilation is CAV (2 speeds) or VAV (varying according to the occupancy rate). The temperature of the incoming air is similar to the outdoor air temperature, except when heat recovery is turned on.

Thermal mass is taken into account in the dynamic simulation and has an influence on ventilative cooling simulations.

Table 7 Advantages and disadvantages of Dial+ software.

| Advantages | Disadvantages |
|---|---|
| Natural ventilation | |
| Simple definition of the room with predefined materials, profiles (ventilation or internal gains) and control strategies (ventilative cooling and blind control) | Only monozone natural ventilation modeling is available. |
| Possibility to simulate single ventilation scenarios (+ stack effect) | Dynamic shading that might influence the airflow rate is not considered directly and needs to be |

[28] https://leso.epfl.ch/software (30/10/2017)

| | |
|---|---|
| | modelled through workarounds. |
| Large customization possibility for the control of natural ventilation, both simple and detailed. | Discharge coefficient is fixed in the software, but can be integrated to the openable ratio of the window. |
| Possibility for hourly and subhourly scheduling of parameters and variables. | Only mean air or operative temperature is simulated. No possibility to see the stratification through the zone. |
| Adaptive comfort diagram provided as an output. | |
| Mechanical ventilation | |
| Hygienic and infiltration rates are predefined depending on the use of the room | Only one ventilative cooling strategy for mechanical ventilation. |

### *8.3.2. Bsim*

BSim[29] is a whole building thermal simulation software that takes account of ventilative cooling through monozone natural ventilation and mechanical ventilation model. For the natural ventilation strategy, single and cross sided ventilation strategy is available. Air flow through the window is calculated combining wind forces and thermal buoyancy. Natural air flow rate varies between basic and maximum air change rates, taking account for temperature difference between indoor and outdoor, window geometry factors, wind influence. The model takes account for openable fraction of the window and discharge coefficient of the opening. Control of the airflow is adjusted to reach temperature and/or $CO_2$ set points. Natural ventilation can be scheduled down to hourly program.

Mechanical ventilation model includes several control strategies, such as, inlet temperature control, zone temperature control, moisture control, recirculation control, night ventilation, VAV control. In the mechanical ventilation model airflow capacity dimensioning is provided that during the simulation may be adjusted according to the demand (VAV). The Mechanical ventilation model includes the following air handling components: heat and moisture recovery, heating coil, cooling coil, humidifier. Component specification is very simple and only dimensioning capacity can be specified. Mechanical ventilation can be defined according to an hourly schedule.

In Table 8 the most important advantages and disadvantages with regards to ventilative cooling simulation in BSim are presented.

With respect to cooling load calculation, the software takes into account thermal mass and dynamic heat storage of all building construction elements.

[29] http://sbi.dk/bsim/Pages/Start.aspx (30/10/2017)

Table 8 Advantages and disadvantages of BSim software.

| Advantages | Disadvantages |
|---|---|
| Natural ventilation | |
| Simple control system based on set values. This can be considered as advantage but in case of sophisticated control strategies the simplicity might be also a drawback. | Presently only monozone natural ventilation modeling is available. Multizone model is in beta version for a very long time. Multizone modeling is though possible but requires special expertise. |
| Possibility to simulate single and cross ventilation scenarios. | Natural ventilation model is not included in the standard package. Additional fee has to be paid. |
| Possibility for hourly scheduling. | Some of the parameters that influence performance of natural ventilation are included in window specification and some in natural ventilation system. There is also no good explanation how parameter related to windows specification ($C_d$, openable fraction, center of the opening) influence air flow rates. |
| Vertical temperature stratification in the room/zone can be taken into account thanks to Kappa model. | There is no possibility to simulate with different discharge coefficients in one simulation. Dynamic shading that might influence discharge coefficient is not considered. |
| Mechanical ventilation | |
| Simple definition of air handling components. Minimizes risk for error or faulty control strategy of the component. Saves time during model development phase. | Simple definition of air handling components. Detailed analysis of component performance is not available. |
| Available wide range of control strategies. | Not so good help file explaining functionality of the control strategies that are available. |
| Many outcome parameters available with hourly resolution. | No bypass function on the heat recovery. |
| | Temperature results not presented with respect to adaptive comfort. |

### 8.3.3. Trnsys

TRNSYS[30] is a simulation environment for the transient simulation of energy systems, including multi-zone buildings. Its most relevant airflow component is called TRNFLOW and is based on an airflow network system but some other simple possibilities for ventilative cooling modelling are also available.

TRNSYS environment can be basically described as being made up of two different cores. The first one is based on an engine that reads and processes input files and iteratively solves the system of equations used. It: it is basically the software architecture, that calls routines and is the 'brain' of the graphic interface of the tool. The second one is a library of components (Types), each of which models the performances of one part of the building and of the HVAC system (pipes, pumps etc.). The engine works routinely calling the library when a specific component is chosen by the user to work in the project.

The key feature of the tool is its open and modular structure. Based on a DLL-architecture, it allows users and third-party developers to easily add custom component models using common programming languages.

The main visual interface is the TRNSYS simulation studio, from which all 'Types' (meaning the single modular element) interact and are connected between each other to generate a model. The TRNSYS simulation engine is programmed in Fortran and is called by an executable (TRNExe) which also allows for an online plotter functionality during the dynamic simulation.

The building visual interface is called TRNBuild. It allows to specify all building structure details as well as internal loads, windows optical and thermal properties, occupancy schedules and others. The building thermal model (Type 56) is based on the heat balance method, and uses conduction transfer functions for the modelling of conduction through walls. The connection in simulation studio between Type 56 and all other types allows for a detailed integration between energy systems modelling and the building itself.

Before discussing the detailed implementation of airflow network in TRNSYS, it is worth mentioning the other simpler options available for modelling ventilative cooling:

- The building model, Type 56, allows for direct input of schedules or detailed profiles of air-flow. In this way, it is possible to either input known data and parameters or input expected values whether possible;
- The equation tool also allows to connect inputs of different Types creating relations between them. It is therefore possible to implement simplified calculations between the most relevant parameters for airflow for any simplified ventilative cooling modelling, as in the case of the 'Wind and Stack' modelling currently used for Energy Plus;
- Mechanical ventilative cooling can be partly modelled directly through simulation studio by performing some assumptions according to the components chosen. Modelling depth can be

[30] http://trnsys.com/ (30/10/2017)

different according to the ability of the modeller and the features of the system to be modelled.

TRNFLOW is the integration of the multizone air flow model COMIS into the thermal building module of TRNSYS.

TRNFLOW is based on air flows between airnodes, from outside into the building (infiltration and through ventilation systems). The data for both models can be input through the user interface TRNBUILD.

The pressure in the zone is a variable in the analysis, assessed according to a continuity equation per zone. Inputs to be given to the system are state variables of the air and local wind speed, direction and pressure.

The thermal and the air flow model are linked as in Figure 54. The information flow between the two models is represented by one room air temperature node and one air flow variable. There are at least as many air temperature nodes as there are thermal zones in the building, and each node as at least one air flow.

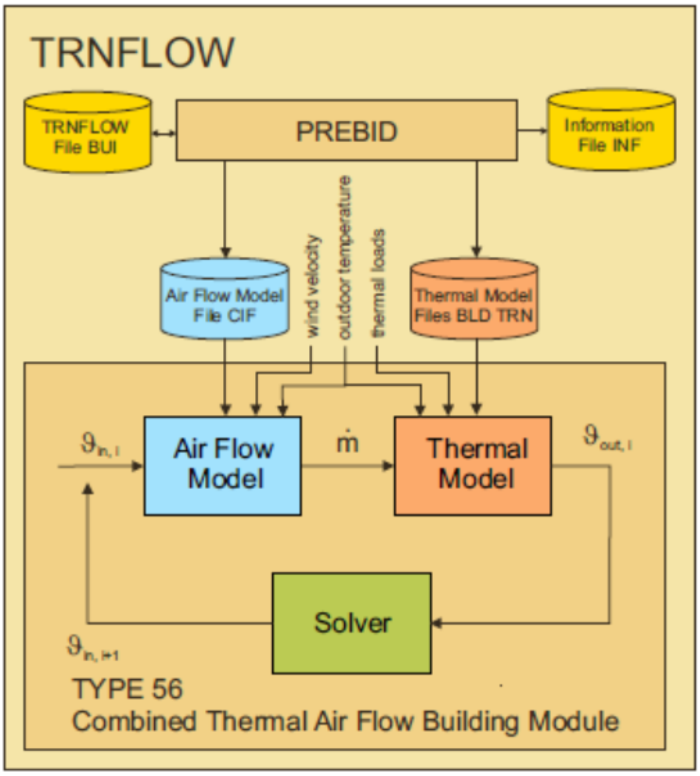



Figure 54 Concept of TRNFLOW.[31]

The TRNFLOW air zone model describes the building as a network of nodes and airflow links. A node is a room volume, with specific conditions. Links can be effectively described as cracks joints, ducts,

[31] http://www.trnsys.de/download/en/trnflow_shortinfo_en.pdf (30/10/2017)

ventilation inlets and outlets. Using mass conservation in each node, a system of non linear equations is built and solved to determine the node pressures and the mass flows in each link.

In Table 10, the most relevant advantages and limits for the tool are summarized.

Table 10 Advantages and disadvantages of TRNSYS software.

| Advantages | Disadvantages |
|---|---|
| Natural ventilation | |
| Large customization possibility for the control of natural ventilation, both simple and detailed. Possibility of developing detailed interaction with windows opening through the connection with calculators and detailed profiles in simulation studio. | The tool is not free and has a higher cost for privates. The educational-research version has substantial discounts. |
| Possibility to simulate single and cross ventilation scenarios and also peculiar designs (e.g. ventilated facades) | Dynamic shading that might influence discharge coefficient is not considered directly and needs to be modelled through workarounds. |
| Possibility for hourly and subhourly scheduling of parameters and variables. | |
| Vertical temperature stratification can be taken into account through the creation of additional air nodes. | |
| Mechanical ventilation | |
| Availability of several simplified components to model mechanical ventilation. Simple definition of air handling components. Minimizes risk for error or faulty control strategy of the component. Saves time during model development phase. | The tool is not optimal in terms of user-friendliness, especially for not experts. It is usually characterized by a steep learning curve, especially in the case of complex HVAC systems in simulation studio. |
| Availability of several detailed components to model mechanical ventilation. Mostly for advanced modelers these components can include also performance maps for HVAC components. | |
| All outcome parameters available with hourly or sub-hourly resolution. | |
| A wide range of control strategies is available | |
| Modular structure that allows for the development of specific user defined components | |

### 8.3.4. EnergyPlus

EnergyPlus[32] is a whole building energy simulation program, free and open source, which models both energy consumption - for heating, cooling, ventilation, lighting, and plug and process loads - and water use in buildings. Its development is funded by the U.S. Department of Energy Building Technologies Office and managed by the National Renewable Energy Laboratory (NREL). EnergyPlus can perform multizone building simulations of integrated, simultaneous solutions where the building response is coupled with the primary and secondary systems. Among other features, it enables advanced fenestration calculations, daylight control, thermal comfort modelling and transient heat conduction.

EnergyPlus is intended to be a simulation engine rather than a user interface. It reads input and writes output text files. Because it is presented as a simulation engine, it is not user friendly and has a steep learning curve. However, several graphical interfaces are under development by third parties and a comprehensive documentation library is provided with each release. The documentation library includes, among others, an input-output reference, which describes input and output of the EnergyPlus files, and an engineering reference, which provides more in-depth knowledge into the theoretical basis behind the various calculations contained in the program. Furthermore, there are several EnergyPlus support services for e-mail, web, and phone support. In addition, several organizations provide general and private/tailored training workshops.

The software is under constant updating process both in terms of execution time, bug fixing and add of new features. DOE releases major updates to EnergyPlus twice annually. The implementation of new features is easy thanks to its well-organized module concept.

***Calculation method***

There are three methods of modelling ventilative cooling in EnergyPlus. The Zone Airflow group objects provide two simplified methods of modelling ventilation based on user-defined assumptions: ventilation design flow rates and ventilation by wind and stack open area[33].

Third method is based on coupled thermal and airflow multi-zone building energy simulations. Airflow Network group objects allow analyzing airflows and pressure differences throughout the building zones, driven by external wind, stack effect and mechanical pressures (fans).

The EnergyPlus model is linked through the airflow network object to the COMIS model. In the COMIS/EnergyPlus link, COMIS is called each time step by the EnergyPlus program by means of an onion coupling approach. Using inside and outside temperatures and the wind pressure distribution at the beginning of a time step, COMIS calculates air flows through cracks and large openings (such as open windows) between outside and inside and from zone to zone. These are then used by the EnergyPlus thermal calculation to determine surface temperatures and zone air temperatures for that time step (which are then used in the next time step to calculate new airflow values, and so on). The

[32] http://energyplus.net/ (30/10/2017)
[33] http://bigladdersoftware.com/epx/docs/8-0/engineering-reference/page-048.html (30/10/2017)

building is represented with one or more well-mixed zones, assumed to have a uniform temperature and a pressure varying hydrostatically, connected by one or more airflow paths. Each airflow path is mathematically described using the Bernoulli equation. A matrix of the equation is constructed and numerically solved. Convergence is reached when the sum of all mass flow rates through all components approaches zero within the tolerance band specified. Airflow paths connect zones, forming a network of ‘nodes‘ (zones) and ‘resistances‘ (linkages). The network can be solved by specifying external climate conditions (temperature, humidity, wind velocity and directions), climate-envelope interactions (wind pressure on the facade) and engineering models for resistances.

The calculation procedure consists of three sequential steps:

- Pressure and airflow calculations;
- Node temperature and humidity calculations;
- Sensible and latent load calculations.

The pressure and airflow calculations determine pressure at each node and airflow through each linkage given wind pressures and forced airflows. Based on the airflow calculated for each linkage, the model then calculates node temperatures and humidity ratios given zone air temperatures and zone humidity ratios. Using these node temperatures and humidity ratios, the sensible and latent loads from duct system conduction and leakage are summed for each zone. The equations for the zone energy balance use the sensible and latent loads obtained in this step to predict HVAC system loads and to calculate the final zone air temperatures, humidity ratios, and pressures.

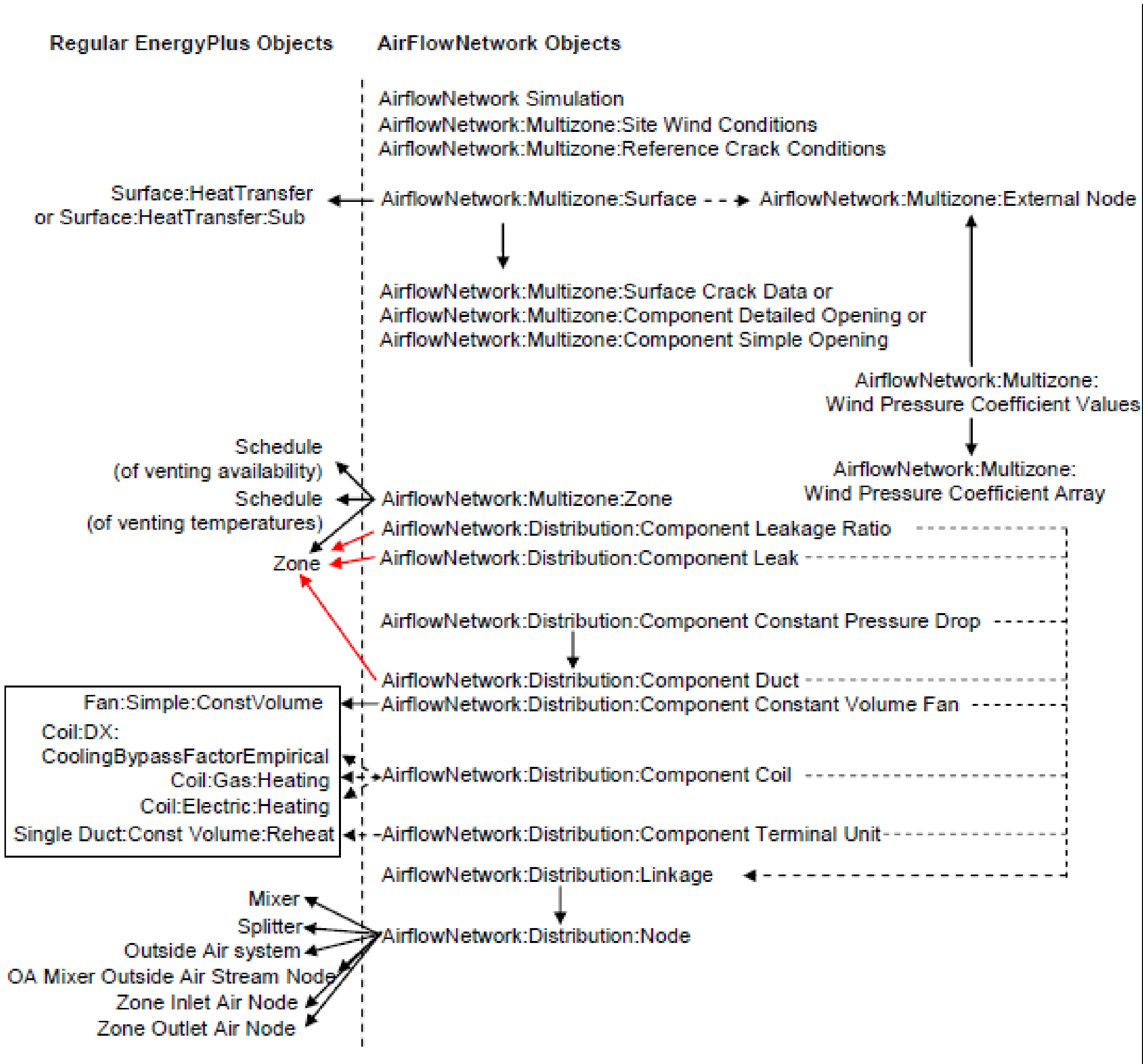



Figure 53 Relationship among Airflow Network objects (right hand side) and associated EnergyPlus objects.[34]

The airflow network extracts automatically the information needed from the building description for thermal modelling. These include zone volume, height, building surfaces geometry and orientation, weather data and terrain type.

The EnergyPlus airflow network model was validated by comparing model results with a large set of high-quality laboratory measurements from ORNL and using measured data obtained from the Building Science Lab (BSL) at FSEC [2].

Table 9 Advantages and disadvantages of EnergyPlus software.

| Advantages | Disadvantages |
|---|---|
| With sufficient input data, employing EnergyPlus in combination with an airflow network can | EnergyPlus has no user interface, therefore it has a steep learning curve. |

[34] https://energyplus.net/documentation (30/10/2017)

| | |
|---|---|
| provide informative predictions of natural ventilation performance during the design phase. | |
| Thanks to the constant software updating process, EnergyPlus is able to model all the most common ventilation strategies (natural, hybrid, mixed mode and mechanical) and controls (based on temperature, $CO_2$, relative humidity, occupancy and others), as well as the performance of ventilative cooling component. | Outputs are provided in form of text files which need post-processing to obtain graphs and to calculate key performance indicators. |
| The program is designed for ease of development. The software is free and open source. Therefore, advanced users can eventually contribute developing new modules for ventilative cooling component modelling. | Natural ventilation rates predicted using the EnergyPlus airflow network are sensitive to a number of key model parameters, which have to be carefully set in the model. These parameters include, in order of significance, the occupant behaviour model for opening control, wind-speed profile, internal heat gains (electrical and lighting), SGHC and envelope conductivity, and wind-pressure coefficients. |
| Input parameters are all explicit and models assumptions are well documented in the documentation library. | |
| EnergyPlus embeds standard recommended thermal comfort models and provides thermal comfort outputs. | |
| EnergyPlus also embeds several room air models to account for non-uniform room air temperatures that may occur within the interior air volume of a zone (i.e. mixing, displacement ventilation, underfloor air distribution, cross ventilation. | |
| Coupling between CFD and EnergyPlus model via open source platform of BCVTB (Building Control Virtual Test Bed). | |

## 8.4. Comparison of software simulation results based on BestTest case building

### *8.4.1. Description of BestTest case*

In this section the building and the measurement protocol are described. Measurements were conducted in the primary school building located in St-Germain, Switzerland. The selected room was a west oriented office highlighted in yellow in Figure 55.

Figure 55 West façade view of the measured building, the monitored room is highlighted in yellow.

The office has a rectangular shape (5.3 x 7.6 x 3.3 m), heavy weight construction, mechanical ventilated HVAC system, and a glazing composition consisting of an openable glass area of 1 $m^2$ and fixed glass area of 7 $m^2$ plus an exterior shading device which covers both the side hung window and the fixed window glass area. The primary school is located in an open area. Due to the asphalt surrounding the building a ground reflectance of 0.1 is assumed as appropriate value.

Temperatures were measured inside, outside and in the adjacent rooms of the investigated room. The measurements were conducted for 6 weeks from 1-7-2015 until 13-8-2015. The data was logged over this period with an interval of 10 minutes. The air temperature in the monitored room was measured at floor and ceiling height. Additionally, in the middle of the room was measured operative temperature. In order to appropriately address the heat transfer between monitored room and the adjacent rooms, temperature sensors were placed also in all adjacent rooms and in the corridor. To acquire insights of the wall surface temperature, a sensor was placed against one of the inner walls. Based on the measured local weather conditions a weather data file was prepared. The solar radiation on site was not measured and therefore, it was collected from an official weather station located 3 km away from the monitored building.

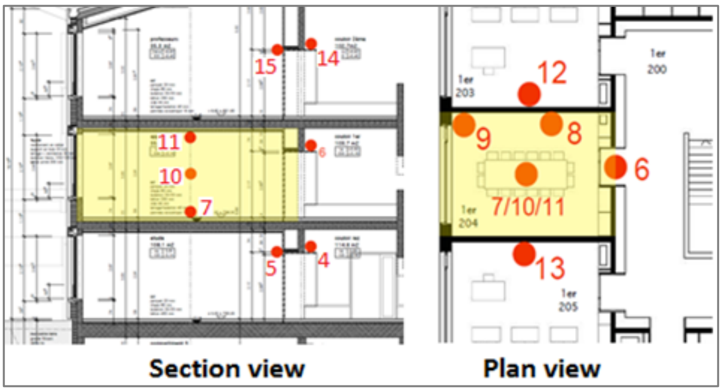



Figure 56 Overview of temperature sensor locations in and around the monitored room.

Measurements are performed under 5 test conditions in order to investigate if software is able to provide reliable results under different ventilative cooling strategies. The different 5 test cases are presented in Table 11. It has to be indicated that during the measuring campaign monitored building was not occupied.

Table 11 Overview of 5 test cases

| Case | Blind position | Mech. vent. | Window position | Internal gains [W] |
|---|---|---|---|---|
| 1 | Standard | On | Closed | 300 |
| 2 | Standard | Off | 35% open during night | 300 |
| 3 | Standard | Off | 62% open permanent | 300 |
| 4 | Standard | Off | 35% open permanent | 300 |
| 5 | Open last day | Off | Closed | 300 |

Here are some specifications of the control settings of each system:

Standard blind position refers to following daily repeated position in standard time:

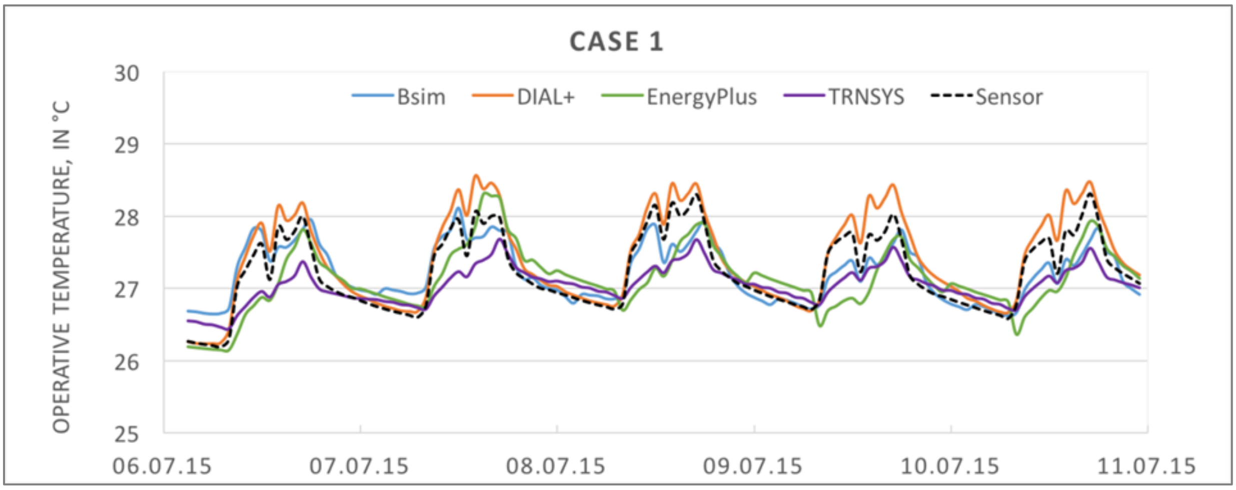
- Blind is completely open at 06:00;
- Blind is closed at 13:00 at pitch angle of 45°;
- Blind is completely closed at 17:00 ;
- Blind is completely closed during the weekend.

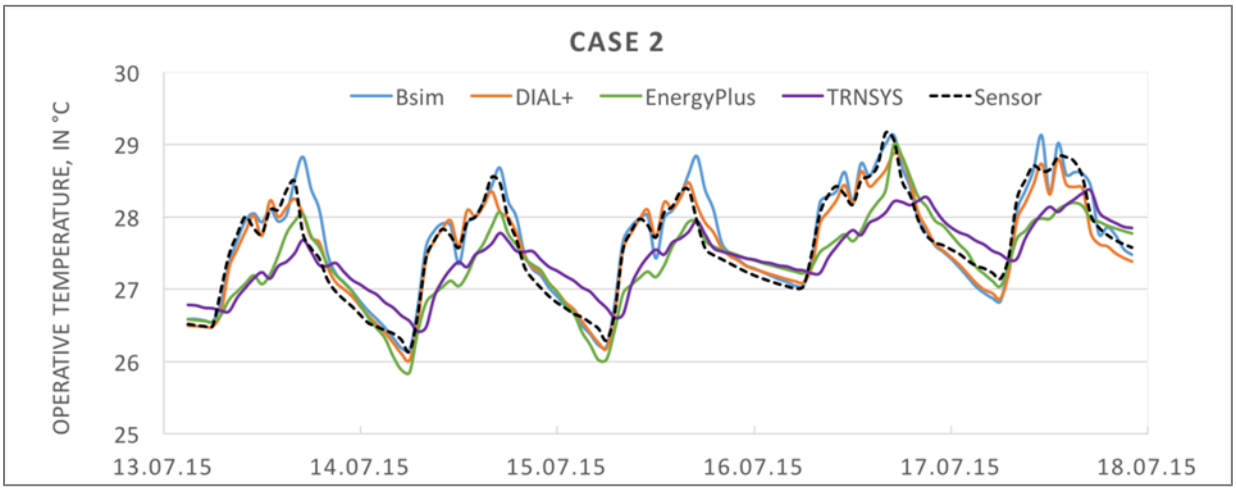
The internal gains resemble people load (building is not occupied during measuring campaign) and follow a daily profile and are in operation from 07:00 to 11:00 and 12:00 to 16:00.

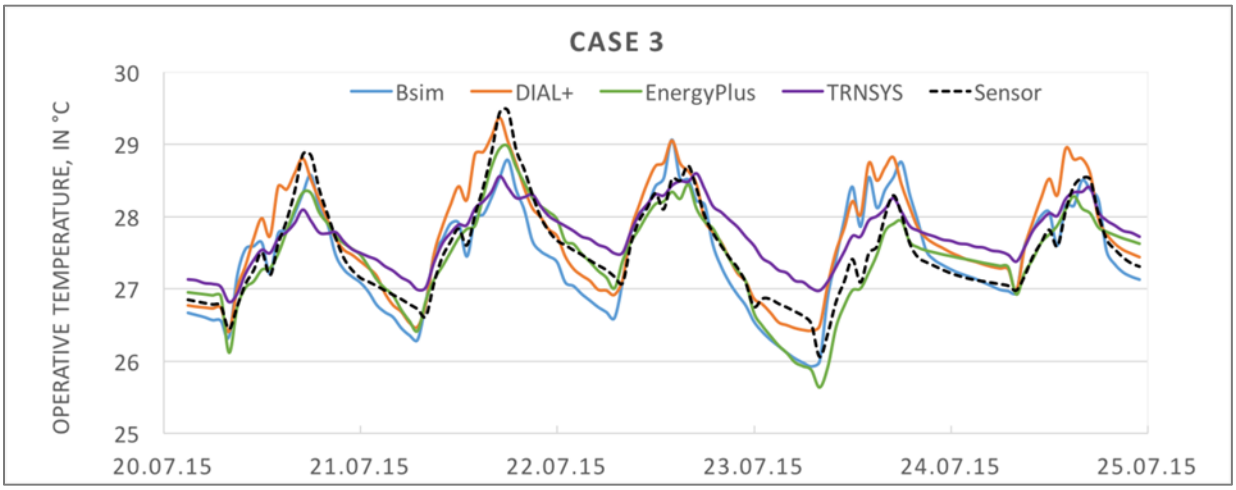
The inlet air temperature from the mechanical ventilation is measured at 26°C at a daily repeated ventilation rate of 150 $m^3/h$ between 07:00 to 16:00 and 62 $m^3/h$ between 17:00 to 23:00. For the remaining hours the ventilation system is not in operation. The open area of the window is calculated as summation of the open areas at the side of the side hung window and bottom triangular. The top triangular in this case is not taken into account because of the lintel.

### *8.4.2. Results*

This chapter presents plots depicting simulated and measured operative temperature for the 5 investigated ventilative cooling strategies for the four simulation softwares: BSim, DIAL+, EnergyPlus and TRNSYS. The simulated operative temperature for each case can be seen in Figure 57.


CASE 1
OPERATIVE TEMPERATURE, IN °C
Bsim
DIAL+
EnergyPlus
TRNSYS
Sensor
30
29
28
27
26
25
06.07.15
07.07.15
08.07.15
09.07.15
10.07.15
11.07.15


CASE 2
OPERATIVE TEMPERATURE, IN °C
Bsim
DIAL+
EnergyPlus
TRNSYS
Sensor
30
29
28
27
26
25
13.07.15
14.07.15
15.07.15
16.07.15
17.07.15
18.07.15


CASE 3
OPERATIVE TEMPERATURE, IN °C
Bsim
DIAL+
EnergyPlus
TRNSYS
Sensor
30
29
28
27
26
25
20.07.15
21.07.15
22.07.15
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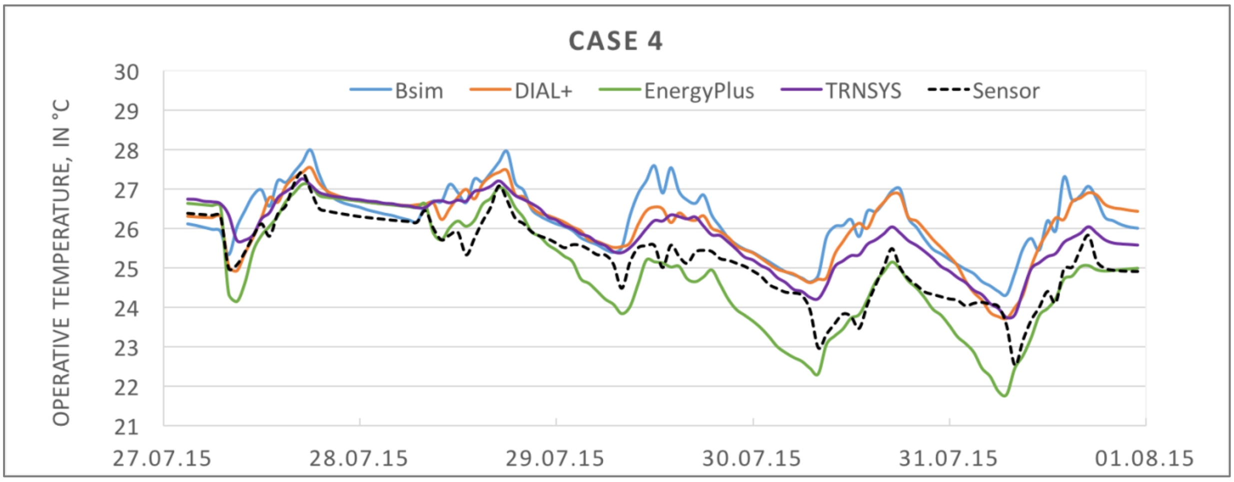


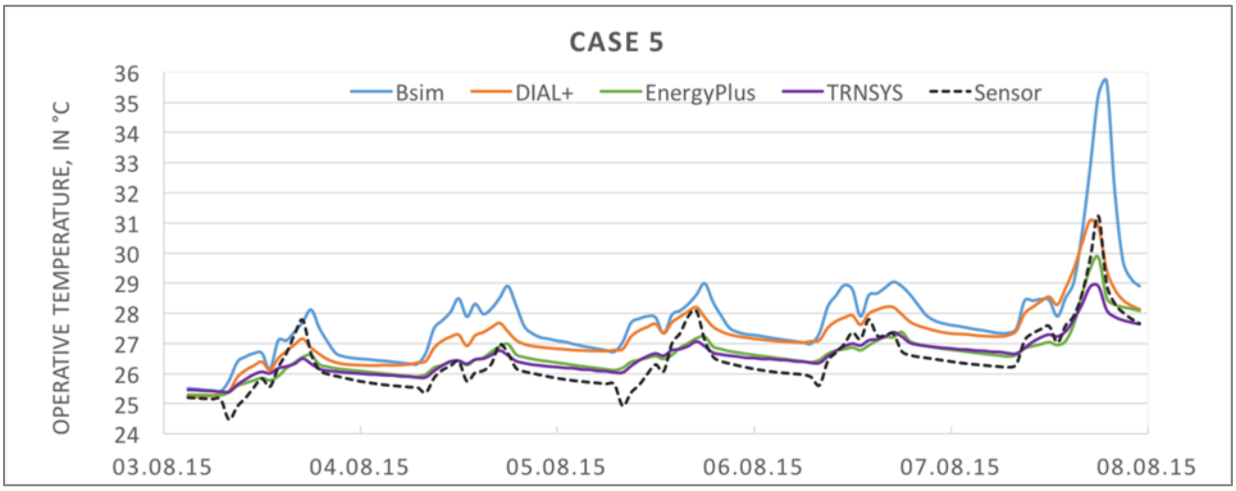


Figure 57 Comparison of the simulated and measured operative temperature for the 5 investigated ventilative cooling strategies for BSim (blue line), DIAL+ (orange), EnergyPlus (green) and TRNSYS (purple).

Table 12 Standard deviation of the obtained results.

| Case | Bsim | DIAL+ | EnergyPlus | TRNSYS |
|---|---|---|---|---|
| 1 | 0.27 | 0.24 | 0.39 | 0.37 |
| 2 | 0.25 | 0.18 | 0.44 | 0.52 |
| 3 | 0.40 | 0.39 | 0.26 | 0.40 |
| 4 | 1.17 | 1.00 | 0.70 | 0.72 |
| 5 | 1.56 | 0.95 | 0.48 | 0.50 |

### 8.4.3. Conculsions

The variation between simulated and measured operative temperature is satisfactory for all considered software. Initial conditions influenced strongly the first days of dynamic simulations results (common problem).

The solar radiation has the largest impact on the operative temperature during daytime. Indeed, global solar radiation was collected from local weather station 4 km away from the simulated room and then converted using the Perez and Ineichen model (1992) to direct and diffuse components. This model has a mean bias error of 14%. Futhermore, presented results confirm that software considered in this study correctly address natural and mechanical ventilative cooling strategies and the use of the blinds.

## 8.5. Final conclusions

The key advantages and disadvantages of each modelling tool were collected in several tables above. The main findings of the performance software analysis presented in this chapter are summarized in the following bullet points:

- The more flexible software out of the 4 analyzed seems to be TRNSYS FLOW and EnrgyPlus. However, they are not so user friendly and have steep learning curves.
- TRNSYS FLOW and EnrgyPlus are open source tools allowing customization and therefore are often used by researchers.
- The tools, such as Dial+ or BSim, allow only monozone airflow calculation, have limited features, but on the other hand they are easy to handle, have more user friendly interfaces and results communication schemes. This type of tools would be more oriented to engineers and designer.
- All analyzed performance simulation tools allow calculation of mechanical and natural ventilation, but not all allow performing multizone airflow modelling.
- All analyzed tools perform combined airflow and thermal modelling.
- Modelling time in all tools is dependent on model size and its complexity, but for the most cases it is minimum.
- Good agreement for all 4 considered software.

## 8.6. References

1) Zhai Z, Johnson M, Krarati M. Assessment of natural and hybrid ventilation models in whole-building energy simulations. Energy Build 2011;43(9):2251-2261.
2) Gu L. Airflow network modeling in EnergyPlus. Internation Building Performance Simulation Association: Proceedings of 10th International Building Performance Simulation Association Conference, Beijing, China. 2007.

# 9. List of Figures

# 10. List of Tables

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