SOLAR-ASSISTED GROUND COUPLING FOR A NATURALLY VENTILATED SCHOOL BUILDING

Malcolm Orme and Agnieszka Isanska-Cwiek
AECOM, Birmingham, United Kingdom
Contact author: malcolm.orme@aecom.com

ABSTRACT

The use of solar-assisted ground coupling to naturally ventilate a primary school located in the East of England has been investigated in a design study informed by computer modelling. Ground coupling using buried air supply culverts can be used to temper ventilation supply air. This can reduce both heating and cooling requirements for buildings. Simulation results are presented for current and projected 2050 future climates. It is concluded that this strategy shows good potential as a zero energy cooling solution provided an integrated design approach is taken. It is seen to significantly reduce overheating without requiring mechanical ventilation or cooling.

INTRODUCTION

A design study informed by computer modelling has been undertaken for a 2,500 m^2 new build primary school located in Peterborough in the East of England. This has set out to investigate the potential for using solar-assisted ground coupling to naturally ventilate the building. The intention was to provide an excellent indoor environment on a year round basis, with good indoor air quality, thermal, visual and acoustic conditions, but with a low environmental impact.

Because of the low driving forces provided by thermal buoyancy and wind pressure differences, all elements in natural ventilation flow paths should be designed so that the individual pressure drops are minimised in the system. Where this is not possible, mechanical ventilation can be used to assist, possibly as part of a 'hybrid' natural and mechanical system (Heiselberg, 2002). This strategy has been applied and monitored in a range of countries with hot and cold climates. Existing examples include buildings constructed in Japan (Kitakyushu University, see Shinada, 2007), Norway (Mediå and Jaer schools, see Delsante and Vik, 2000), and Sweden (Slättäng school, see Delsante and Vik, 2000).

Ground coupling can temper ventilation air during hot or cold periods. The use of natural ventilation with buried underground ducts or culverts is generally only suitable for sufficiently large air flow requirements, due in part to the high dynamic pressure losses encountered with air supply ducts of small cross-sectional area. Ventilation of school classrooms is one such application for which large air flow rates are required.

In general, high internal to external temperature differences or wind speeds during winter can lead to high driving forces, such that they can provide sufficient natural ventilation air flows. However, particularly during the daytime in summer, temperature differences and wind speeds can be much lower and only provide low natural ventilation driving forces. To counter this for ground coupled systems, driving forces can be increased for example by including 'solar chimneys' and 'solar attics' terminating the ventilation air flow paths on the extract side of the system, ensuring that sufficient flow rates are maintained through thermal buoyancy to provide cooling with tempered outdoor air. This approach is the basis of the design study described.

Design standards

The indoor environmental performance analysis in the design study is based on:

- Indoor air temperatures calculated on an hourly basis
- Indoor air quality (IAQ) calculated on an hourly basis in terms of carbon dioxide arising from occupants
- Daylight performance and acoustics (not reported here)

The design was developed to take into account these issues and to meet and preferably exceed minimum standards or requirements. The study did not include moisture transport, except in terms of ventilation-related transfers involving outdoor air and moisture from occupants.

The extent of overheating in school buildings in England is currently assessed with reference to Building Bulletin 101 (DfE, 2006). The stated criteria for teaching and learning spaces are that from 1st May to 30th September during occupied hours:

A. *There should be no more than 120 hours when the air temperature in the classroom rises above 28°C.*

B. *The average internal to external temperature difference should not exceed 5°C.*

C. The internal air temperature when the space is occupied should not exceed 32°C.

To show at design stage that a school building does not excessively overheat, it should be demonstrated by calculation that two of these three criteria must be met.

Carbon dioxide arising from occupants ('bioeffluent CO_2') is commonly used as an indicator of general IAQ in buildings. BB101 recommendations for IAQ in a teaching environment in are:

- *The average concentration of carbon dioxide should not exceed 1500 ppm.*
- *The maximum concentration of carbon dioxide should not exceed 5000 ppm during the teaching day.*
- *At any occupied time, including teaching, the occupants should be able to lower the concentration of carbon dioxide to 1000 ppm.*

The non-teaching areas have also been assessed against the BB101 overheating and IAQ criteria.

DESIGN PROCESS AND OPTIMIZATION

An integrated design approach was adopted from the very early stages of the project. This approach ensured the performance for indoor daylight penetration, thermal comfort, indoor air quality and acoustics was assessed and then revisited as required during design development.

The brief was for a design that whenever possible significantly exceeds the minimum indoor environmental performance standards set out in BB101 and other official guidance. The design process began with an initial building concept of a classroom block with rooms leading from two sides of a central corridor. From the outset it was proposed to use high level glazing at the back of the rooms to enhance daylight levels. From this, the idea of an enclosed 'solar attic' to assist with natural cross ventilation then followed. The case studies described in Delsante and Vik (2000) provided the inspiration and confidence to investigate a strategy based on air supply culverts and solar chimneys. Figures 1(a), 1(b) and 1(c) illustrate some of the concepts investigated, progressing from simple strategic concepts based on a four classroom block through to more developed concepts for the whole building.

To design a low pressure natural ventilation system, it is crucial to make full use of available natural driving forces. So, the system components including the air intakes, culverts, transfer openings and risers, solar attic, and the solar chimneys were optimized accordingly. In fact, during design development, the building form itself was adjusted to assist with the optimisation. Various options were examined, including:

- level of thermal mass used in conjunction with night ventilation,
- glazing properties to manage solar gains,
- glazed conservatory buffer spaces adjacent to classrooms, if present,
- corridor width,
- classroom height,
- air supply culverts: number, length, vertical cross-sectional area and position of air intakes,
- solar attic: number, compartmentalisation, and
- solar chimneys: number, height and plan cross-sectional area.

Following on from this, improved strategies and related design options for the building were then suggested. It is noted the building room layout was being arranged in parallel with the optimisation process. The building form itself was also heavily influenced by the ventilation strategy adopted.

Ventilation strategy

The integrated and optimised design concept established for the building is represented in Figure 2. The natural ventilation strategy relies on stack ventilation, as shown in Figure 3 (summer day and night) and Figure 4 (winter day only). Outdoor air enters by natural ventilation through two fixed air intake openings through above ground intake towers to two large underground air supply culverts serving certain areas of the building, one running NW-SW and the other NE-SE.

Air is introduced to teaching and learning areas (all classrooms, a library and two halls) through the culverts connected to the conservatories or to the rooms directly depending on the season via risers. During winter, air is routed via the conservatory spaces for passive solar heating. CO_2 control is assumed year round, with temperature control also used during summer. The system is additionally used for secure night ventilation during summer. Double doors connect the classrooms to conservatory spaces, with further double doors to outside for use during mid-season conditions. Air exhausts naturally from the rooms through acoustically lined ducts ('acoustic fingers') into a fully glazed 'solar attic' leading to five glazed solar chimneys. The solar attic is an unheated roof space above the corridors, which is fully glazed on the outside roof slopes. The north-east façades of the solar chimneys were assumed to be opaque to absorb solar radiation, so increasing internal air temperatures to improve the natural stack effect. For all non-teaching and learning areas such as offices, the ventilation strategy relies on single sided ventilation through windows. These spaces are not connected to the culverts or to the solar chimneys.

The culvert vertical cross-section dimensions are each 2.0 m by 2.0 m and the upper surface of these is located 2.0 m below ground level. Each classroom has a total of 1 m^2 riser area from one of the culverts. The solar chimneys are each 2.6 m by 2.6 m in plan and 12.0 m high from ground level.

The construction is reasonably thermally massive, with a screed covered concrete ground floor, plastered blockwork internal partitions and rendered blockwork external walls with external insulation. The roof is generally thermally lightweight on the inside of the insulation layer, which is lined with acoustic tiles, and there are also green roofs.

SIMULATIONS

Software

Dynamic thermal and ventilation simulations were carried out with IES Virtual Environment v6.2 (IES, 2009). This integrates a number of modules based around a common three-dimensional geometric model. The modules used for this study were 'Apache-Sim' for thermal simulation calculations, 'Suncast' for solar shading analysis and 'Macroflo' for natural ventilation assessment. Macroflo takes into account buoyancy induced pressure differences and external wind flows to calculate bulk air flow rates and is coupled with Apache-Sim.

Model geometry

The model geometry is shown in Figure 2. The analysed school building is single storey throughout, principally with a ‘central corridor’ layout with classrooms and other spaces on either side. Each classroom is connected to an unheated conservatory space, which creates a buffer between the indoor and outdoor environments. There are two individual risers from one of the culverts for each classroom. The classrooms are connected through the solar attic to the solar chimneys.

Weather data

The following weather files were used to represent:

1. The 'current climate' - hourly CIBSE 2005 Test Reference Year (TRY) for Nottingham (CIBSE, 2005), in accordance with BB101.
2. A 'future climate' for 2050 for a 60 year building design life - hourly PROMETHEUS high emissions scenario, 90-percentile 2050 TRY (Eames et al, 2011), derived from UK Climate Impacts Programme 2009 results.

In addition, two ground temperature profiles at 3 m depth have been created:

1. A ‘current climate’ profile - This is based on ground temperatures published in a current climate TRY (Eames et al, 2011), but adjusted with a 3 month offset to better match the temporal distribution of profiles from measured data (Garcia-Suarez et al, 2005).
2. A ‘future climate’ profile for 2050 - Using the relationship between the air temperatures in the current weather file, the air temperatures the future weather file, and the ground profile derived for the current climate, ground temperatures were adjusted to align with the future climate projection.

The assumed ‘current’ and ‘future’ ground temperature profiles adjacent to the culvert walls at 3 m depth and average air temperatures are summarised in Figure 5.

Model assumptions

In the analysis a highly insulated and reasonably airtight building has been assumed. The following assumptions for the fabric thermal performance were made:

- external walls: U-value 0.13 $W/m^2{\cdot}K$
- ground floor: U-value 0.10 $W/m^2{\cdot}K$
- roofs: U-value 0.10 $W/m^2{\cdot}K$
- glazing: U-value 1.3 $W/m^2{\cdot}K$; g-values 0.37 where solar control and 0.56 where standard.

Solar control glazing was assumed in between classrooms and the solar attic and for the outside of conservatories to limit unwanted gains. Standard glazing was assumed for outside of the solar attic and solar chimneys to increase air temperatures in these spaces.

The underground culverts were modelled as uninsulated rectangular concrete ducts surrounded by soil in direct contact with the ground, with the seasonally varying ground temperature profiles assigned to the external surfaces consistent with the weather file. For modelling convective heat transfer between air masses inside the culvert and the adjacent culvert walls, dynamic heat transfer coefficients were applied as well as throughout the whole building. The convective heat transfer coefficients are calculated as functions of surface orientation, air-surface temperature difference and mean culvert (or room) air velocity.

The pressure drop through the culvert was calculated using the multi-zone airflow analysis software CONTAM (Walton and Dols, 2010). To take account of a calculated total resistance pressure drop of 1.2 Pa along each culvert (at a ventilation rate of 2.9 m^3/s), the cross section of each culvert was locally constricted in the model to 1.9 m x 1.9 m at a single location.

DISCUSSION OF RESULTS

The results for the current and projected future climates for overheating in the teaching and learning areas are shown in Table 1. For the current climate, all teaching and learning spaces are significantly better than the minimum BB101 overheating requirements. For the future climate, all teaching and learning spaces still meet all three BB101 criteria, except for one of the halls. (For this latter space, it was concluded that decreased solar and internal gains would be needed.) Annual CO_2 concentrations are seen to be within the BB101 criteria for both the current and projected future climates (Table 2).

The results for overheating for the current climate in non-teaching spaces (cellular offices, meeting and other rooms) and for the projected future climate are also shown in Table 1. For the current climate, two of the BB101 overheating criteria are met as required, but none are for the future climate. For the non-teaching spaces, CO_2 concentrations are found to fulfil the BB101 criteria for both the current and projected future climates (Table 2).

Figure 6 shows air temperature distributions through the natural ventilation system during a hot summer week (31st May to 6th June) for a typical classroom. Although the external air peaks at 34.4°C, the classroom temperature peaks at only 26.7°C. During this period, the ground temperature at 3 m depth is assumed to be 12.0°C. Also in this period, the maximum temperature reduction found between the external air and culvert air temperature is 14.1°C. It is observed the IES Virtual Environment assumes full internal mixing and so the heat transfer between the culvert walls and the ventilation air may be overestimated. It can be seen in Figure 6 there is about a 3 to 5 hour time lag between the peak external and culvert air temperatures.

By way of comparison, the study also investigated an alternative 'minimum standard' school building design, which did not include the solar-assisted natural ventilation system or ground coupling. This design relies on natural cross ventilation and is able to meet the BB101 overheating criteria for the current climate. But, for the projected future climate, the results presented in Table 3 show that all spaces failed to meet the BB101 overheating criteria.

It is remarked that the client, Peterborough City Council, did not proceed with the construction of the building in the form discussed in this paper due to capital cost and construction programme limitations.

CONCLUSIONS

As part of a design study for a primary school, an optimised design has been realised and demonstrated by simulation to significantly exceed minimum standards for avoiding overheating in current- and projected future climates. Specifically, solar-assisted natural ventilation together with ground coupling using underground culverts has been confirmed to be a promising strategy to provide 'zero energy' cooling. In addition, indoor air quality was calculated to be satisfactory with the proposed approach. While a minimum standard design can meet required standards in the current climate, it is unable to provide the necessary performance under future climate change.

The optimisation approach followed is consistent with current design practice, but it could be enhanced by more detailed modelling of the buried underground culverts concerning ground to air heat transfer and system pressure losses. In addition to the present study, further work would be needed to estimate energy savings from the proposed design.

An integrated design approach proved to be essential in simultaneously achieving multiple performance requirements. Moreover, integrated design of the whole system is crucial to enable it to function correctly.

ACKNOWLEDGEMENTS

This paper is based on work commissioned by the Technology Strategy Board and Peterborough City Council. The views expressed in this publication are those of the authors and not necessarily those of the Technology Strategy Board or Peterborough City Council. The authors would like to thank Will Pitt, formerly of AECOM, and Mike Phillips, Enterprise Peterborough, with whom they worked on the design study.

REFERENCES

CIBSE (2005), Current CIBSE TRY/DSY Hourly Weather Data Set - Nottingham, CIBSE, London, UK.

Delsante A. and Vik T.A. (Editors) (2000), Hybrid Ventilation: State of the Art Review, ECBCS Annex 35 'Hybrid Ventilation in New and Retrofitted Office Buildings', Aalborg University, Aalborg, Denmark.

DfE (2006), Building Bulletin 101: Ventilation of School Buildings, Department for Education, London, UK.

Eames M., Kershaw T. and Coley D. (2011), 'On the creation of future probabilistic design weather years from UKCP09', BSERT, 32 127-142.

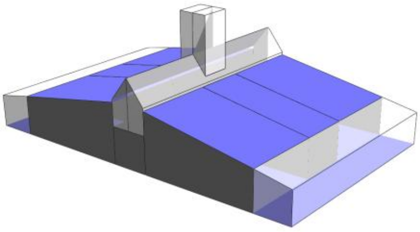
Garcia-Suarez A.M., Butler C.J. and Morrow B. (2005), Meterological Data Recorded at Armagh Observatory: Volume 4 - Daily, Monthly and Annual Soil Temperatures 1904-2002, Armagh Observatory Preprint Series, Armagh, UK.

Heiselberg P. (Editor) (2002), Principles of Hybrid Ventilation, ECBCS Annex 35 'Hybrid Ventilation in New and Retrofitted Office Buildings', Aalborg University, Aalborg, Denmark.

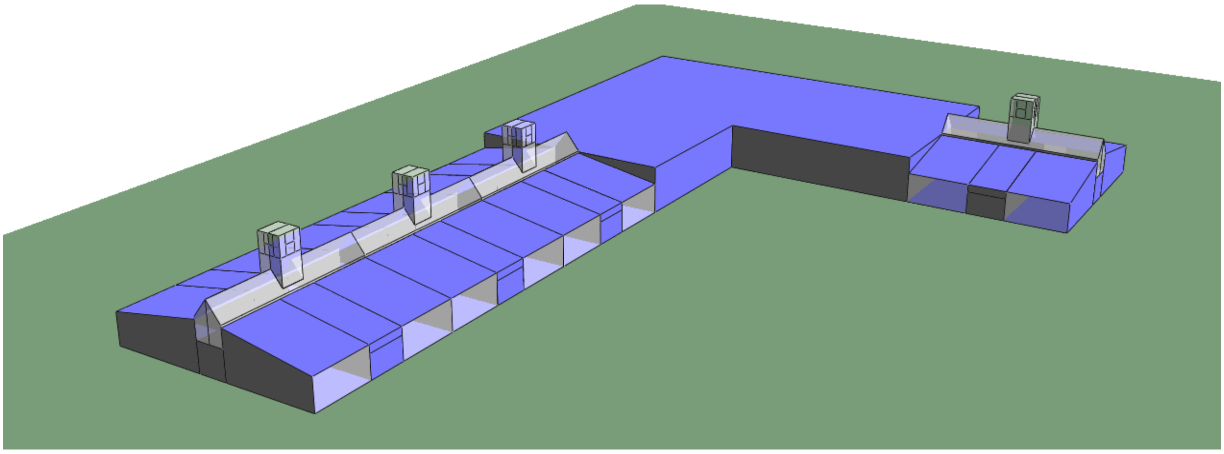
IES (2009), VE Overview: General Help Topics Virtual Environment 6.0, Integrated Environmental Solutions, Glasgow, UK.

Shinada Y., Kimura K.-I., Katsuragi H., Song S.K. (2007) 'Natural Ventilation System for a School Building Combined with Solar Chimney and underground Pit', in Proceedings of Clima 2007 Wellbeing Indoors, FiSIAQ , Espoo, Finland.

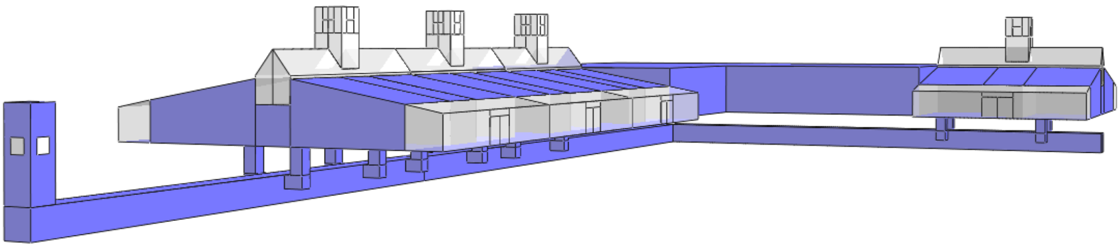
Walton G. N. and Dols W.S. (2010), CONTAM User Guide and Program Documentation, NISTIR 7251, NIST, Gaithersburg, MD, USA.



(a) An early design strategic concept (4 classroom block)



(b) An early design whole building concept



(c) A whole building concept option (single air supply culvert)

Figure 1 Design optimisation building concepts

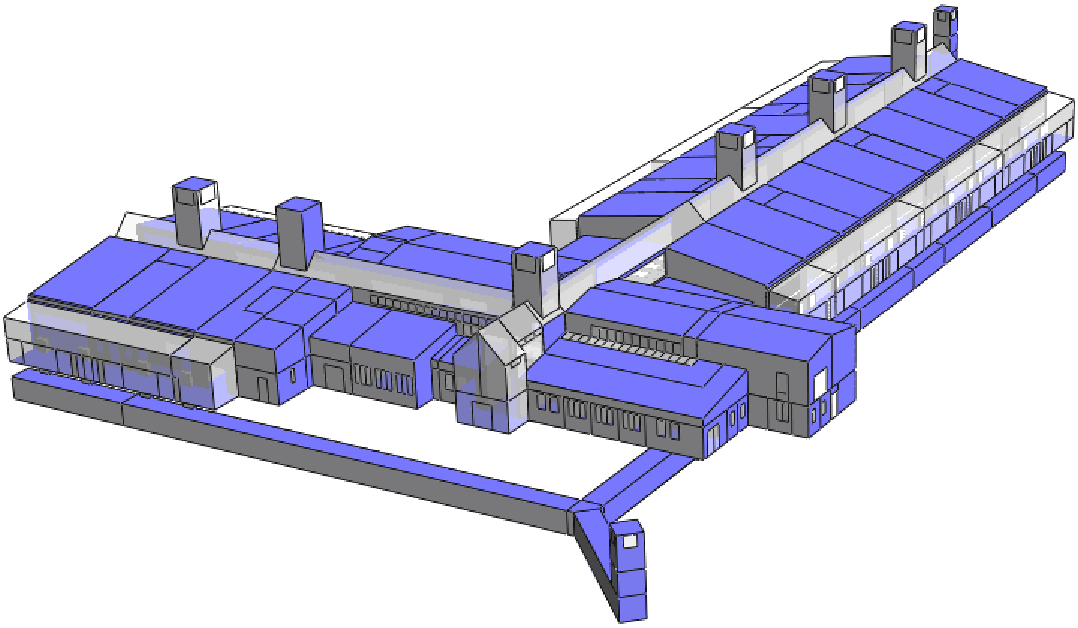


Figure 2 Integrated and optimised design concept

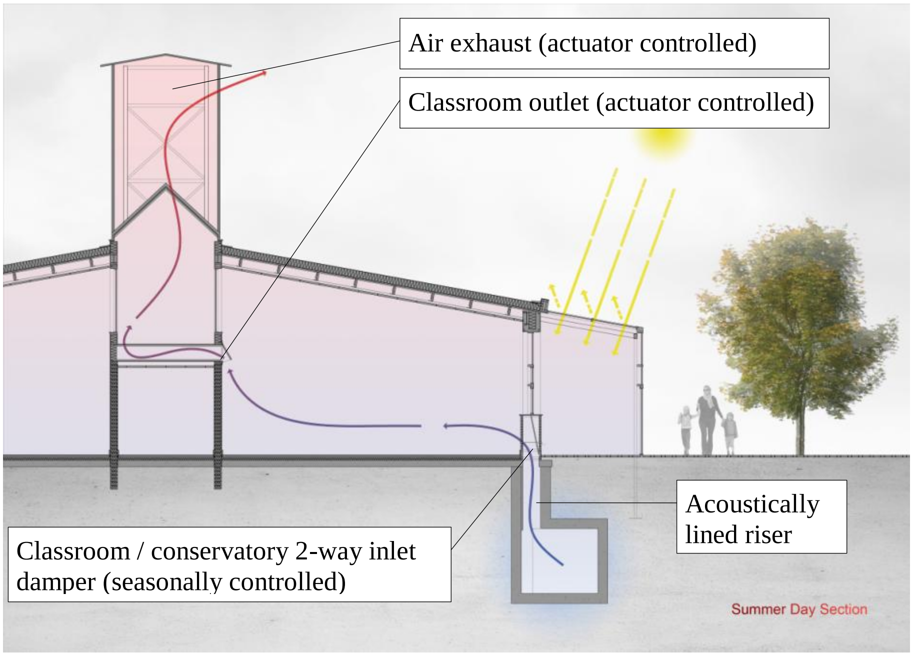


Figure 3 Natural ventilation strategy in summer period (Picture source: Enterprise Peterborough)

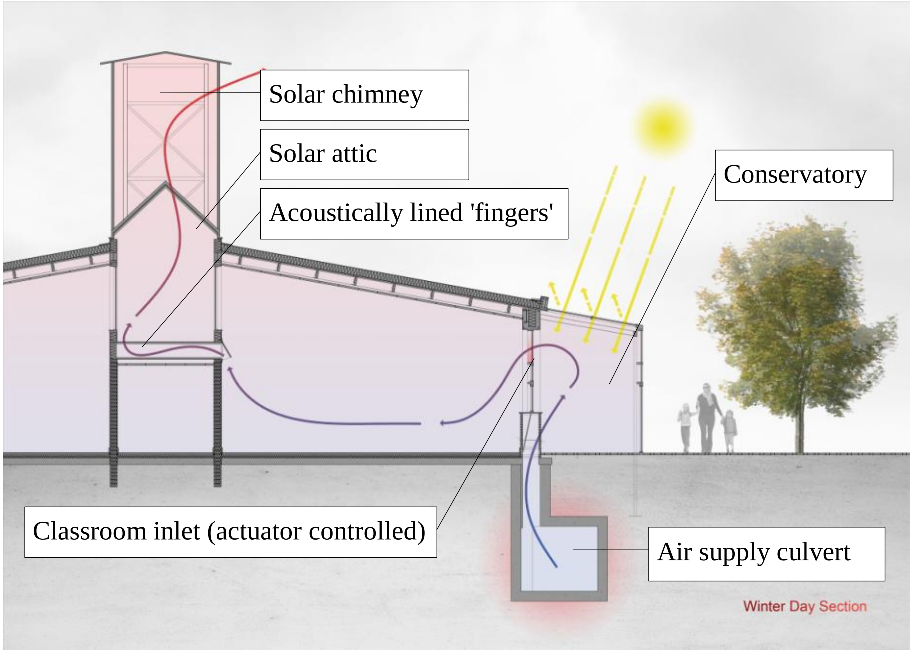


Figure 4 Natural ventilation strategy in winter period (Picture source: Enterprise Peterborough)

Table 1 Overheating results with underground culverts and solar chimneys (09:00 - 15:30, 1st May – 30th September)

Room Type	BB101 Criterion A [h]	BB101 Criterion B [°C]	BB101 Criterion C [°C]	Performance against criteria
Simulation weather data: CIBSE Nottingham 2005 TRY				
Classroom (worst case)	**0**	**4.7**	**26.6**	**"Pass"**
Hall (worst case)	4	4.8	28.8	"Pass"
Library (worst case)	0	3.9	25.8	"Pass"
Non-teaching (worst case)	29	7.0	29.5	"Pass"
Simulation weather data: PROMETHEUS Nottingham 2050 high emissions 90-percentile TRY				
Classroom (worst case)	**115**	**3.5**	**31.9**	**"Pass"**
Hall (worst case)	148	3.4	34.1	"Fail"
Library (worst case)	80	2.8	32.0	"Pass"
Non-teaching (worst case)	377	6.0	34.8	"Fail"

Table 2 Bioeffluent CO_2 concentration results with underground culverts and solar chimneys (09:00-17:30, 1st January – 31st December)

Room Type	Average CO_2 concentration [ppm]	Maximum CO_2 concentration [ppm]	Number of hours when CO_2 > 1000 ppm [h]
Simulation weather data: CIBSE Nottingham 2005 TRY			
Classroom (average)	**906**	**1777**	**726**
Hall (average)	720	1398	218
Library (average)	771	1507	393
Non-teaching areas (average)	611	1245	234
Simulation weather data: PROMETHEUS Nottingham 2050 high emissions 90-percentile TRY			
Classroom (average)	**932**	**2246**	**791**
Hall (average)	663	1200	131
Library (average)	767	2270	444
Non-teaching areas (average)	583	822	186

Table 3 Overheating results for an alternative 'minimum standard' design (09:00 - 15:30, 1st May – 30th September)

Room Type	BB101 Criterion A [h]	BB101 Criterion B [°C]	BB101 Criterion C [°C]	Performance against criteria
Simulation weather data: CIBSE Nottingham 2005 TRY				
Classroom (worst case)	**8**	**5.1**	**29.7**	**"Pass"**
Hall (worst case)	31	5.5	31.6	"Pass"
Library (worst case)	83	7.9	30.8	"Pass"
Non-teaching (worst case)	52	7.3	30.8	"Pass"
Simulation weather data: PROMETHEUS Nottingham 2050 high emissions 90-percentile TRY				
Classroom (worst case)	**135**	**3.3**	**35.2**	**"Fail"**
Hall (worst case)	205	4.2	36.8	"Fail"
Library (worst case)	454	6.8	35.4	"Fail"
Non-teaching (worst case)	379	6.2	36.0	"Fail"

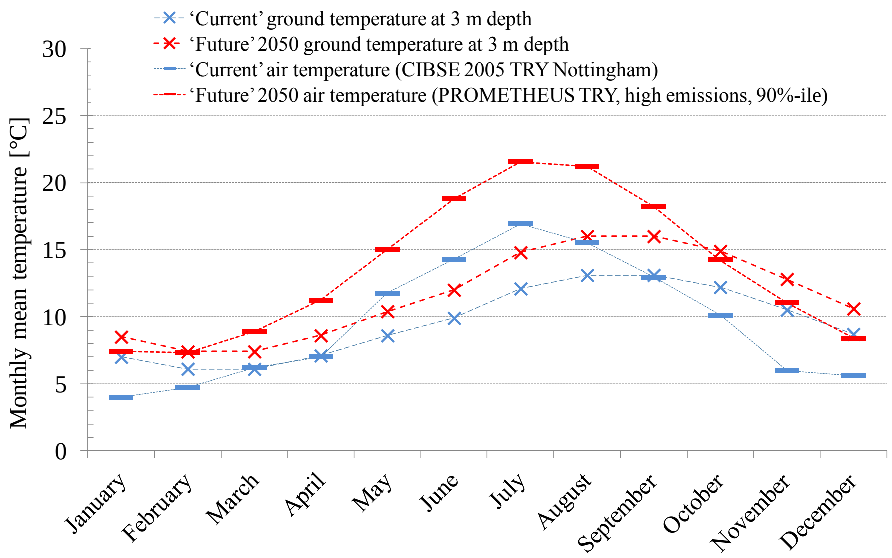


Figure 5 Monthly mean air- and ground temperature at 3 m depth for the current and future climates

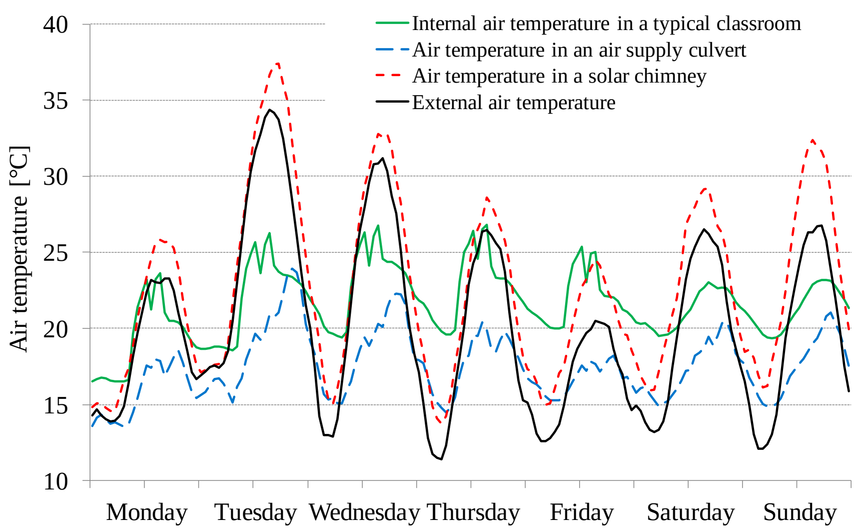


Figure 6 Example air temperatures in the natural ventilation system during a hot period (31st May to 6th June)