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EXPERIMENTAL AND CFD RESEARCH ON THE THERMAL PERFORMANCE OF THE AIR COOLED SLAB SYSTEM

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ABSTRACT

This paper presents an air cooled slab system (ACS) specially designed for use in multi-storey steel framed buildings. The system works by passing air through ducts in the trapezoidal hollow section of the steel/concrete composite floor, so the mass of the concrete slab can be used to store both heat and coolth at different parts the diurnal cycle. Since the ACS system uses the thermal capacity of concrete, it has considerable potential for reducing or even eliminating the need for mechanical cooling. This paper presents a CFD model of the ACS system that was developed to understand the performance of the system under different operating conditions. The model was validated with experimental data.

INTRODUCTION

Most modern office buildings need constant air-conditioning in summer in order to remove heat gains and achieve acceptable levels of indoor thermal comfort. In moderate climates, one promising approach used to reduce the air-conditioning energy demand of office buildings without reducing comfort is passive cooling by night ventilation in conjunction with utilising the thermal mass of the building.

Conventional concrete buildings contain most mass in the exterior walls, solid internal partitions and also in floors. Modern large buildings have removed the mass from walls by using light weight construction including glass facades or insulated cladding systems. Therefore most of the thermal mass in the structure is in the floor slabs.

Traditional passive cooling by night ventilation means passing cool night air through the office space to ensure absorption of the coolth by the building elements, such as floor, walls, furniture etc. However, this system suffers from a lack of control of the amount of coolth absorbed and discharged by the office space. As a result the office space is often overcooled and in the morning, this can cause comfort problems. One way to minimize this effect is to introduce the cooling to the inner parts of the building elements e.g. by embedding air ducts within the floor/ceiling slabs. It not only allows the coolth to be discharged slowly into the office space during the day, but also allows the daytime air to be cooled by passing it through the ducts before entering the office space instead of using air conditioning.

The first ACS system was used in the late 1970's, in Sweden (Winwood et al., 1997) and it utilised the hollow cores within pre-cast concrete floor slabs. This system known as the ThermoDeck has been used in a number of locations throughout northern Europe (Barton et al., 2002). This paper presents an ACS system that uses a light-weight composite floor, which is more suitable for modern, steel-framed buildings.

THERMAL MASS

The ACS system uses the thermal capacity of the steel/concrete composite floor. The amount of storable and dischargable thermal energy provided by the slab is determined by three factors:

- the amount of cooling introduced into the building at night,
- the heat exchange between the concrete slab and the passing air,
- the capacity of the slab to store the transferred heat.

The first factor is dependant on the local climate. The effectiveness of thermal storage is acceptable where the diurnal variation of ambient temperatures exceeds 10K (Holmes, Wilson, 1996). The climate in the UK has a large diurnal temperature swing, approximately 12K, where the night minimum temperature during summer is much lower than 22ºC. It means that there is a considerable potential for coolth storage during the night and possibly enough to eliminate the need for an air-conditioning system in the building.

The amount of heat exchange between the concrete and the passing air is increased by maximizing the exposed surface area and by ensuring turbulent flow.

Since a deep trapezoidal profile steel decking section is used for the ACS system it increases the contact surface between passing air and the concrete. Proper design of the height and shape of the air path ensures turbulent flow. In addition the air ducts are specially designed to increase the turbulence of air flow by using the ribbed surface profile of the steel decking. It should be noted that increasing air turbulence results in an increased pressure drop, so the fan energy required will be greater. Therefore a reasonable balance was struck between heat transfer enhancement and fan energy consumption.

The ability of the slab to store the transferred heat /coolth depends on thermal mass. Thermal mass can be characterized by the thermal diffusivity (α) of the building material, which is defined as:

$$\alpha = \frac{\lambda}{\rho c_p} \tag{1}$$

Both specific heat capacity and thermal conductivity give rise to what is known as the thermal mass effect. In large heavyweight materials, it can take a significant amount of energy to heat up the surface by 1K. This is because much of the energy is actually absorbed deeper into the material, being distributed over a larger volume. With a lot of energy incident on the surface, this absorption can continue until it travels through its entire width, emerging on the inside surface as an increase in surface temperature.

Generally, the more dense a material is the higher its thermal mass will be – i.e. the better its ability to store heat. The material must allow heat to flow through it, so its thermal conductivity should be good. But if its conductivity is too high (e.g. steel) energy is absorbed and given off too quickly to create the lag effect required for diurnal moderation.

The storage capacity of the slab depends on the thickness of its effective penetration depth. In a typical building with natural ventilation only a relatively thin depth of concrete (typically 50mm to 75mm) is effective for efficient heat transfer and storage (Holmes, Wilson, 1996). If the flow inside the slab is enhanced, the thermal capacity of the slab increases significantly, as is shown in Figure 1.

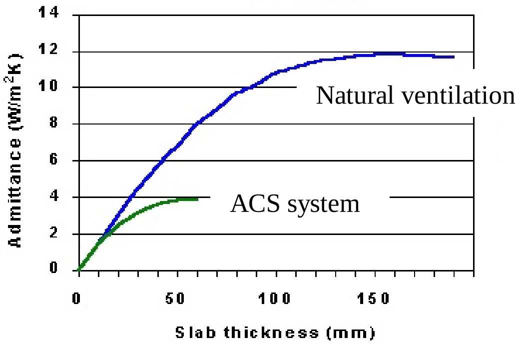

Figure 1 Performance ACS system v natural ventilation

The slab responds to the changes in the diurnal temperature cycle, which can be approximated by a sinusoidal cycle with a period of 24 hours. The ability of the slab to exchange heat and coolth over a 24-hour cycle is measured by the thermal admittance (CIBSE Guide, 1999), which is defined as:

$$Y = \frac{Q_{swing}}{T_{swing}} \tag{2}$$

Thus the larger the admittance, the greater the heat/coolth load that can be absorbed by the slab for a given temperature change.

For an ACS system calculations of admittance for increasing thickness of concrete slab indicate that a maximum value is reached at a slab thickness of around 150mm, as shown in Figure 1. This result indicates that there would be little advantage in increasing the thickness of a slab more than 150mm on a purely thermal mass basis, assuming a constant 24-hour temperature cycle. The larger thickness may become significant only in weekly or seasonal cycles.

The zone of thermal admittance of the ACS system for one channel is shown in Figure 2.

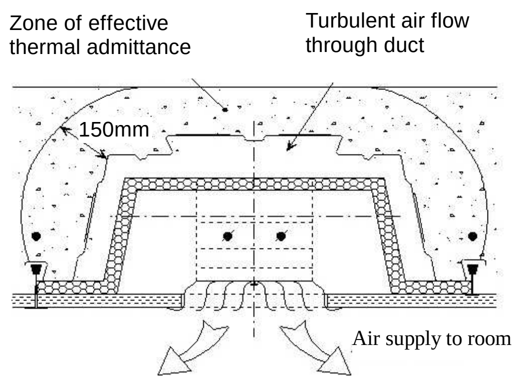

Figure 2 Thermal admittance to concrete slab

The effective storage of the slab is important not only because of the large amount of heat or coolth that can be stored but also the night cooling period can be minimized, because the coolth is absorbed in a shorter time. As a result the time required for running fans is decreased.

FULL_SCALE EXPERIMENTAL SET-UP

Experimental tests have been carried out at Corus Swinden Technology Centre in the UK to determine the thermal performance of the ACS system. The work used a full-scale slab of a typical floor construction measuring 3.75x12m shown in Figure 3.

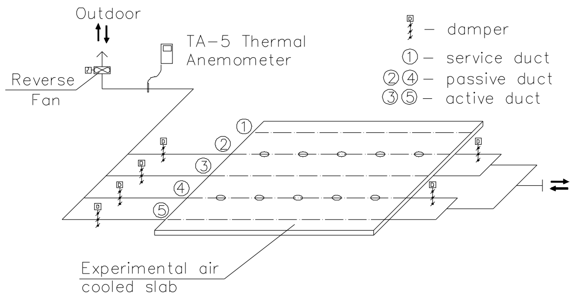

Figure 3 Schematic diagram of the test rig

The slab construction consisted of five channels using the Corus Slimdek SD225 decking and concrete. The overall depth of slab was 320mm. Two of these channels were used as a passive ducts, two as active ducts and one was designed as a service duct as is shown in Fig. 4.

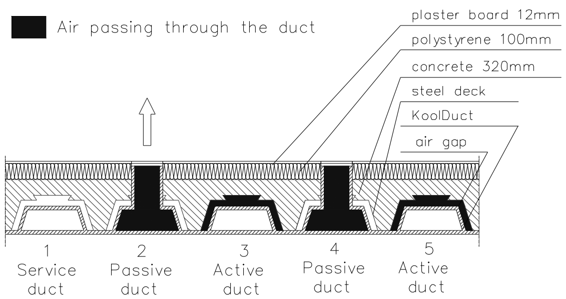

Figure 4 Cross-section of the ACS system

To create the air channels in the active and passive ducts the KoolDuct system was employed. The geometry of the air gap in the active ducts was determined by previous tests carried out at Oxford Brooks University (Ogden, Kendrick, 2002).

To isolate the test rig from unwanted external influences, such as solar radiation or changing air temperature duringday at the laboratory, the slab top was covered with polystyrene and plasterboard and the sides with Rockwool. The air supply ducts were also insulated with Rockwool.

A full-scale measurement of the slab temperature was carried out under daily cyclic outside air temperature.

Data from each test was recorded at 12-minute intervals using a Solatron Scorpio 200 channel data logger. Data collection equipment produced both recorded output of all the sensors and a continuous display of all the quantities being measured so that each test could be monitored as it progressed.

Temperatures of the concrete surface were measured at a total of 42 locations. The concrete surface temperatures were measured using epoxy encapsulated thermistor sensors in a stainless steel housing with vinyl insulated leads.

The measurement points are shown on the example at cross-section "c", which is 4.5m downstream from the slab inlet (Fig. 5).

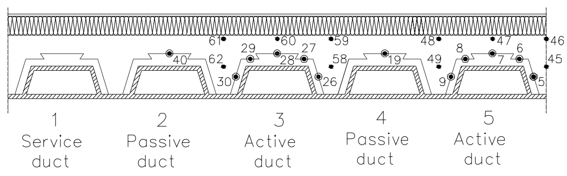

Figure 5 Cross-section "c"

Before use, the temperature sensors were calibrated across the range: 10ºC to 35ºC, which corresponds to the approximate operating range of the floor system. They were calibrated in a water bath with stirrer against a calibrated RTD and a maximum tolerance of ±0.2ºC was observed

The temperature of the concrete slab was measured at a total of 26 channel locations using the same thermistor probes as those used to measure the surface temperatures.

The air temperatures were measured using thermistor sensors with a vinyl shielded microphone cable, which is used to support and keep them in the right position as well as providing thermal isolation between the sensor and the steel.

The volumetric air flow was determined by using the average air velocity. To ensure the most accurate estimate of average velocity, ten measurements were taken in the cross-sectional area of the round duct (Fig.3) and two traverses across the diameter of the duct at right angles to each other were made. Locations of the measuring points were determined using the log-Tchebycheff method, so the readings were taken at the centre of annual rings of equal area. The traverse was made more than 7 duct diameters downstream from any air disturbance. The local velocities were measured with a TA-5 Thermal Anemometer.

EXPERIMENTAL RESULTS

The presented results are from test which was carried out during the weekend 17th/18th October 2004 at Swinden Technology Centre. The thermal performance of one active channel (3) was measured under stable airflow (160l/s) and variable slab inlet air temperature, which was changing according the outside temperature.

The results shown in Fig.6 indicate that the air passing through the channel is warmed up approximately to 2K (T74-T73) during night.

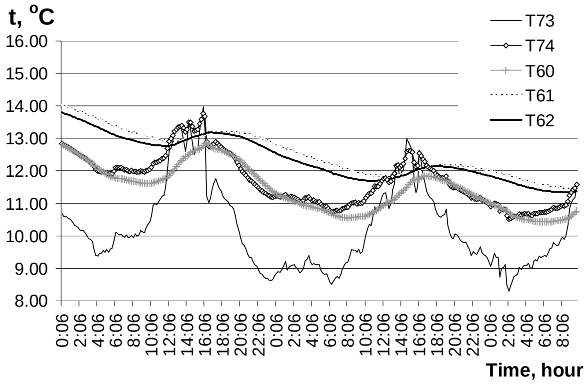

Figure 6 Air and slab variation at T73, T74, T60, T61, T62

The slab temperatures measured at two depths, 60mm and 195mm from the upper surface of the concrete slab (the total depth of the slab is 320mm). The purpose of these sensors was to determine the temperature distribution through the concrete under transient slab inlet air temperature. Thermistor T60, placed at the closest to the steel decking (45mm above) responds to the transient air temperature the fastest (Fig.5).

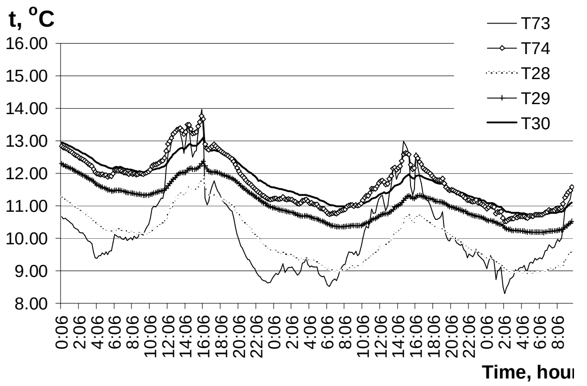

Figure 7 Air and slab variation at T73, T74, T28, T29, T30

Figure 7 presents the results, when the temperature sensors were mounted on the decking surface, essentially they are measuring the concrete surface temperature. The results indicate that the heat transfer between the passing air and the concrete is highest at the top part of the channel.

The preliminary experimental tests show the potential of the ACS system to store coolth, however there are still various issues that need to be investigated.

CFD MODELLING

Simulations were performed with the commercial CFD software – CFX 5.7. This code is based on a finite-volume method and it resolves the Reynold-Average Navier-Stokes equations for each control volume in the region of interest.

Geometry and mesh

The slab channel geometry is shown on the Figure 8 and was considered to be a component of a larger slab structure. Due to the symmetry of the physical domain, the computational model had a simplified geometry.

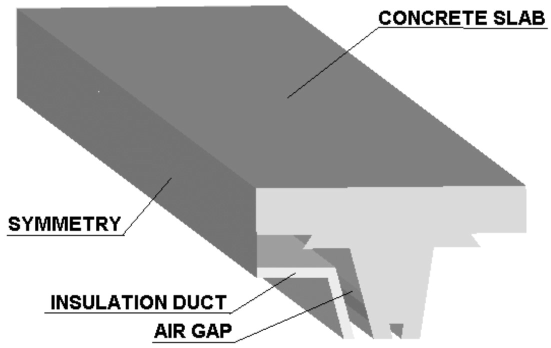

Figure 8 Geometry of the CFD model

The domains were divided into a non-uniform, structured mesh. Summary of mesh sizes is presented in Table 1.

Table 1
Summary of mesh size

DOMAIN	NO. OF NODES	NO. OF ELEMENTS HEXAHEDRONS
Concrete	313 236	293 000
Air gap	115 794	104 750
Insulation	33 264	26 875
TOTAL	462 294	424 625

The presented computational grid, which is shown in Figure 9, becomes finer near the solid walls. The effect of the grid spacing on the computed results was checked by increasing the total number of elements to about 550 000, and no obvious difference for the temperature and air velocity distribution was observed.

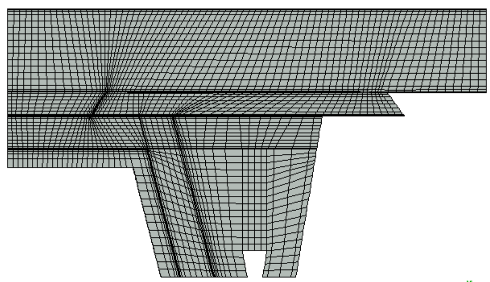

Figure 9 Three-dimensional mesh

Description of the CFD model

The time was discretised into 12-minute intervals.

The thermo-physical properties of air are dependent on temperature, pressure and moisture content. Since the change in values of these parameters is very slight and simulating these dependencies would have greatly increased the time required to converge a solution, the model was defined with the constant properties listed in Table 2.

The thermo-physical properties of the concrete and the insulation are given as well in Table 2.

Table 2
Physical properties of materials used in the model

MATERIAL	ρ kg/m3	λ W/m2K	C_P J/kgK
Concrete slab	1950	1.9	840
Air	1.185	0.028	1004.4
Insulation	60	0.018	1210

The inlet boundary is defined by setting a mass flow.

Temperature profiles for the inlet air were based on the weather data from the CIBSE Guide. Profiles were delivered for the month of August, which is the warmest month in the UK. The inlet air temperatures measured during testing were used to validate the CFD model.

At the outlet, the average static pressure was constrained to atmospheric.

Only one-half of the geometry was modeled, which saved memory and calculation time. The symmetry boundary condition is a free slip wall, which flow cannot cross, but the boundary doesn't impede flow parallel to it.

The numerical simulations for this research are done using a three-dimensional CFD model. In the simulation a standard k-ε model is used which is based on both a transport equation for turbulent kinetic energy k and a transport equation for the dissipation of turbulent kinetic energy ε.

To solve buoyancy the Boussinesq model is employed. Since the change in air density over the expected range of conditions is relatively small, a constant fluid density is assumed.

Validation of the CFD model

Validation of the model was performed using the experimental data from 3-day tests. Data from the first day were used to establish the initial temperature of the slab in CFX simulation.

The CFD model was compared with the experiment in terms of: the temperature of air leaving the slab and the temperature distribution at the cross-section "c" of channel number 3 (4.5m downstream of the slab inlet). The maximum values are presented in Table 3.

Table 3
Maximum disagreement between the CFD and experiment results

LOCATION	AVERAGE DISAGREEMENT %
Tout	5.0
T28	4.2
T29	5.5
T30	5.0

It can be concluded from Table 3 that the CFD model of the ACS system has produced an accurate representation of the slab's behaviour.

RESULTS AND DISCUSSION

The validated CFD model was used for a series of numerical simulations to investigate the slab's performance with:

- various insulation options (both surfaces exposed, the upper surface insulated and both surface insulated),
- various air flows,
- various thermal properties of concrete,
- various convective heat transfer coefficients.

A total of six cases were studied based on various combinations of above parameters.

Various insulation options

Since the coolth exchange is inside the channels there is no need to expose the concrete surfaces to the interior of a building. However, when additional night ventilation through openings is employed, the top of the slab shouldn't be insulated.

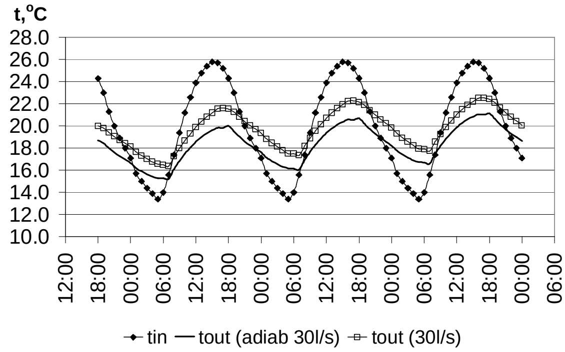

Figure 10 Diurnal temperature profiles produced with varying insulation

Simulations were therefore performed to investigate the slab's performance with top surface exposed and with both surfaces insulated.

Figure 10 shows that the heat transfer was only slightly affected by the insulation of the top of the slab. The outlet temperature for the slab with top surface exposed differs from the insulated slab by only about 4%. However it should be noted that when the slab is not insulated the building has a greater thermal stability.

Various thermal properties of concrete

The thermal parameters of concrete may vary as a result of the physical-chemical make up. The typical values of three various type of concrete are shown in Table 4 (CIBSE Guide, 1999).

Table 4
Concrete parameters

CONCRETE	ρ kg/m3	λ W/m2K	C_P J/kgK
Heavy weight	2000	1.3	840
Medium weight	1350	0.59	840
Light weight	630	0.2	840

Lightweight concrete, containing pulverized fly-ash, or other light weight aggregates is being used increasingly in steel-framed buildings to keep structural weight to a minimum value. It has a density around 32% of that of heavyweight material and a thermal conductivity of just over 15% of that of heavyweight concrete.

It can be concluded from Fig.11 that concrete parameters such as density and thermal conductivity have an influence on the thermal behaviour of the slab. The outlet temperature for the slab made with heavyweight concrete differs from that made with lightweight concrete by about 10%.

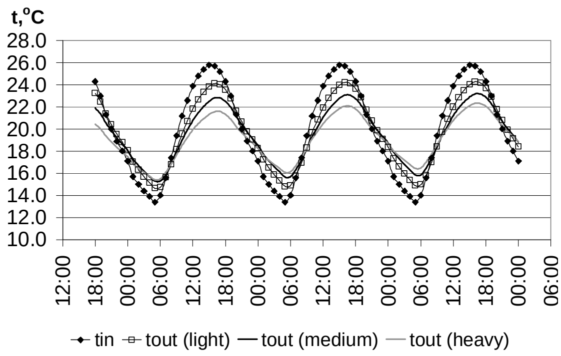

Figure 11 Diurnal temperature profiles produced with varying concrete parameters

The heavyweight concrete slab maintains a more stable temperature during the daily cycle, making it more suitable for use as a modifier of the internal climate in passive cooling systems.

Various convective heat transfer coefficients

Experimental testing of the ACS has demonstrated that a value of heat transfer coefficient up to 50 W/m^2K can be observed (Ogden, Kendrick, 2002).

Calculation of air temperature leaving the slab at various values of convective heat transfer coefficient (hc) shows that this property has a much greater influence than any properties of the material itself, as shown in Fig. 12.

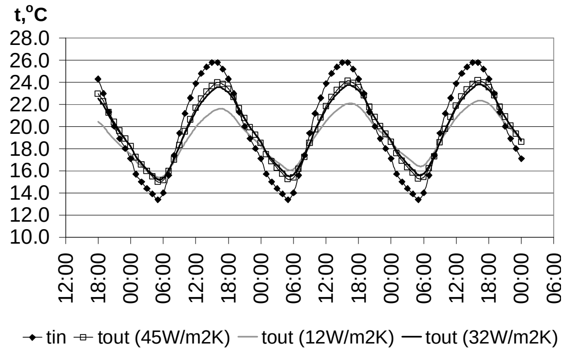

Figure 12 Diurnal temperature profiles produced with varying heat transfer coefficient

The outlet temperature for the slab rises about 13% by increasing heat transfer coefficient from $12W/m^2K$ to 45 W/m^2K.

If the surface resistance to heat transfer can be overcome, improved thermal storage can be achieved in the slab. In practice, mechanical ventilation is required to achieve reasonable values of heat transfer coefficient.

However the actual values of heat transfer coefficient depend not only on the air flow rate but also on the level of turbulence created in the air flow in the channels, which is a function of surface roughness and obstructions in the air flow path. It means that the ducts should be specially designed to approach this aim.

Various air flow

Airflow rates used in the simulation were chosen based on typical supply air change rates when the system is installed in office buildings. The maxiumum air flow (120l/s per duct) corresponds to six air changes in the room.

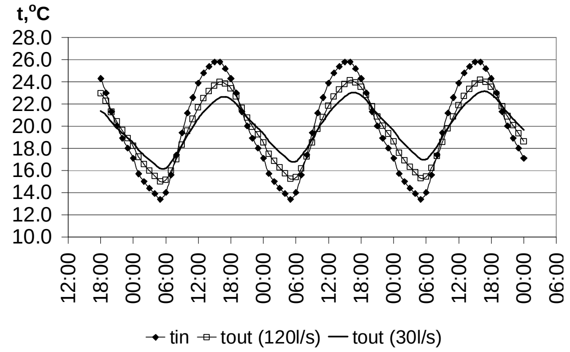

Figure 13 Diurnal temperature profiles produced with varying airflow

The effect of different air supply rates was investigated by simulating flows of 30 l/s (25%) and 120 l/s (100%) per channel producing the outlet air temperature profiles shown in Figure 13.

Since the air flow has significant impact on the heat transfer coefficient value, the results are comparable to the previous section, which shows that this parameter has a strong dependence on the thermal performance of the ACS.

Air cooling rate

The data from simulation was used to calculate the total rate of air-cooling produced by one active channel over the period of test, using the equation:

$$Q = m \cdot c_p \cdot (t_{inlet} - t_{outlet}) \quad (3)$$

Fig. 14 presents the cooling rate over meter of the duct, which vary from 11 to 32W/m.

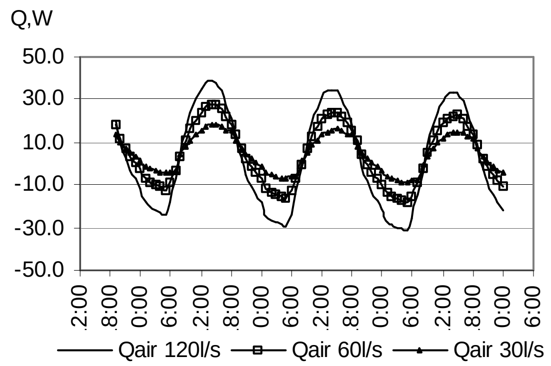

Figure 14 Diurnal air-cooling rates per 1m of the channel with varying airflow

However the calculated air-cooling rate is difficult to translate into equivalent values, which could be used to estimate air-cooling load to the room. In this case thermal simulation techniques are needed.

CONCLUSION

The CFD model of the ACS system has been constructed and shown to produce an accurate representation of the ACS's behaviour.

Various analyses of different factors such as: insulation options, air flow rates, thermal properties of concrete, convective heat transfer coefficient have shown that the efficiency of the system will have a strong dependence on convective heat transfer coefficient and the air flow rate.

Therefore it is suggested to use an advanced control strategy to achieve more efficient performance of the ACS system.

Further work is also required to examine the thermal response of rooms and building under variable weather conditions (outside temperature, solar radiation) and operational parameters of the ACS system.

NOMENCLATURE

α	thermal diffusivity, m^2/s
λ	thermal conductivity, W/mK
ρ	density, kg/m^3
c_p	specific heat capacity, J/kgK
Y	thermal admittance, W/m^2K
Q_{swing}	difference between heat gain to the space at time *t* and the daily mean value, W/m^2K,
T_{swing}	difference between the space temperature at time *t+dt* and the daily mean value, K.
Q	cooling rate, W
m	mass flow rate of air, kg/s
t_{in}	slab inlet temperature, ºC
t_{out}	slab outlet temperature, ºC
k	turbulence kinetic energy, m^2/s^2
ε	turbulence eddy dissipation, m^2/s^3

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REFERENCES

Barton P., Beegs C.B., Sleigh P.A.: A theoretical study of the thermal performance of the Thermodeck hollow core slab system, Applied Thermal Engineering 22 (2002) 1485-1499

Environmental design CIBSE Guide A, London, 1999

Holmes M.J., Wilson A.: Assessment of the performance of ventilated floor thermal storage system, ASHRAE TRANSACTION 1996, vol. 102, pp. 698-707

Ogden R.G, Kendrick C.C.: Use of fabric thermal storage to provide passive cooling in steel framed commercial buildings, The International Conference on steel in Green Building Construction, Orlando, USA, March 1998

Ogden R.G, Kendrick C.C.: Improved System for Energu Efficiency in Steel Construction, Report to Department of the Environment, Transport & the Regions and Corus, Document RT820, Version 03, June 2002

Ren M.J., Wright J.A.: A ventilated slab thermal storage system model, Building and Environment, Vol.33, No. 1, pp. 43-52, 1998

Review of low Energy Cooling technology, IEA-BCS Annex 28

Winwood R., Benstead R., Edwards R.: Advanced fabric energy storage I: Review, Building Services Engineering Research and Technology, 18(1) 1-6 (1997)

Winwood R., Benstead R., Edwards R.: Advanced fabric energy storage II: Computational fluid dynamics modelling, Building Services Engineering Research and Technology, 18(1) 7-16 (1997)