Exploiting the thermal mass in an energy efficient building – a comparison exercise between IES Apache and TRNSYS models

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SUMMARY

Cooling modern office buildings significantly contributes to their CO_2 emissions during summer. One possible approach to improve their summer energy performance in moderate climates would be to cool the building's floor slab by passing cold air through it at night. During the day, warm ambient air is passed through the cold slab and thus it enters the air-conditioning system of the building at a lower temperature. In order to evaluate the energy performance benefits of such a concept, a combination of full-scale experimental studies, Computational Fluid Dynamics modelling (using ANSYS CFX) and network modelling (using IES Apache and TRNSYS) has been performed. Both IES Apache and TRNSYS models agree well in their predictions and the energy benefit of the concept is clearly demonstrated.

INTRODUCTION

Many modern office buildings need constant air-conditioning in the 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. 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 the 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 in the morning and may require additional cooling to bring temperature to a comfortable level. 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 slab.

The Air Cooled Slab (ACS) concept used in this work is based on a composite flooring system with air ducts, which would offer both an integrated service capability and a thermal storage system. Extensive experimental, Computational Fluid Dynamics and Whole Building Energy studies of the ACS were carried out under the European RFCS funded EEBIS project and details can be found in [1].

Throughout the nighttime during hot periods, cold outside air is passed through the ducts embedded in the slab thereby cooling it. Throughout the daytime, when cooling loads increase due to solar and internal gains and ambient temperature rise, external air is pre-cooled by passing it through the slab. The storage capacity of the slab depends on its thickness and 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

[2]. If the flow inside the slab is enhanced, the thermal capacity of the slab increases for a 24-hour temperature cycle to around 150mm [3], which is illustrated in Figure 1.

The climate in the UK has a large diurnal temperature swing, approximately 12K, with the night minimum temperature during summer being much lower than 22ºC. It means that there is a considerable potential for "coolth" storage during the night time and possibly enough to significantly reduce the need for an air-conditioning system in the building.

Figure 2 illustrates the three modes of operation that characterise the use of the ACS. In the night cooling mode, cold ambient air is forced through the channels using mechanical ventilation. During this mode the temperature of the slab is reduced to approximately 18-20ºC. In the morning, when the ambient air has a low temperature, it is used directly for ventilation (mechanical or natural, mode 2). The passive cooling mode 3 is activated during day when ambient temperature rises and solar and internal heat gains cause the office temperature to cause thermal discomfort. Warm ambient air is passed through the slab and could either be directly introduced (via floor or ceiling diffusers) in the office space or additionally cooled by the air-conditioning system of the building.

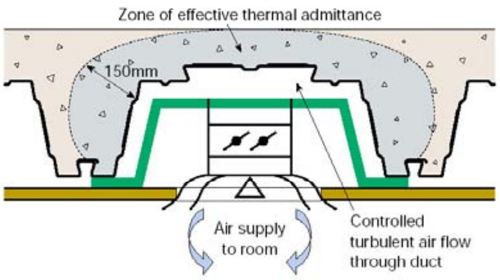

Figure 1 Zone of effective thermal admittance of the ACS (Variation with ceiling diffuser and distribution in the active trough)

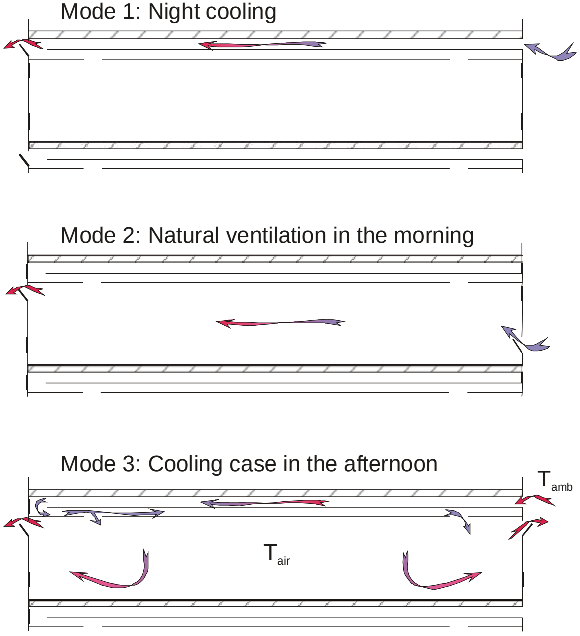

Figure 2 Running modes of ACS

Figure 3 shows a cross section of the floor slab. In the inactive channels air does not have a direct contact with the slab and serve as distribution ducts only (Figure 3)

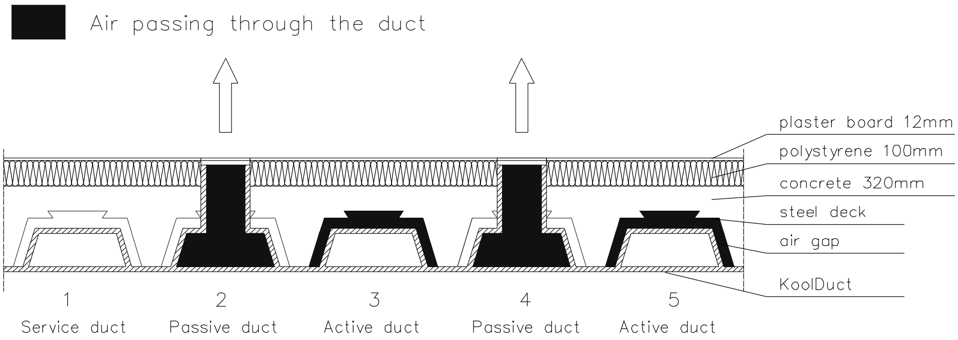

Figure 3 Cross section of the ACS. In the active ducts air has direct contact with the slab. The passive ducts are only used for distribution of the air into the office space and in these air does not have a direct contact with the slab. An additional duct is used for services.

This article presents a numerical study of the performance of the ACS in a realistic energy efficient building. The main objective of this article is to compare the performance of the ACS using two different modelling approaches embedded into two different software packages for building energy analysis (TRNSYS and IES Apache). The rest of the article is organised as follows: the modelling section presents details of the models and their validation followed by a results section. The article concludes with a discussion section.

METHODS

Development of a reduced model of the ACS for use with a whole building simulation models

As mentioned in the introduction of the article a series of experiments were performed on a full scale ACS prototype (12m long, 5 channels) and these results are presented elsewhere [1]. In parallel with the experiments a Computational Fluid Dynamics (CFD) model of the ACS was developed and validated against the experimental data [1]. The results from the CFD model have been used to create a submodel of the ACS for use with IES Apache and this is described in the rest of this section.

The Apache environment provides models for standard HVAC elements, such as rooms, boilers, chillers, heating and cooling coils, fans, chilled ceilings, but a user defined model is needed to account for the effects of the thermal storage of the slab. The ACS is modelled as a separate room, which behaves in a similar way as the ACS. Apache is a zone model in which flow variables are assumed to remain constant within a given zone, which normally represents a room. Each wall of this room is assumed to be at a uniform temperature and a heat transfer coefficient with respect to the average room temperature accounts for the convective heat transfer to the wall.

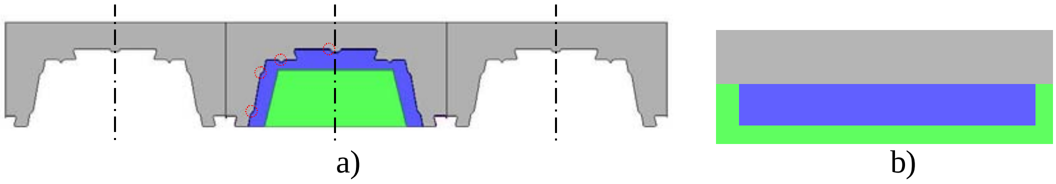
a) b)

Figure 4 Reduction of the ACS model for use with Apache. a) sketch of a cross section of the ACS; b) simplified model of ACS for use with Apache. The grey, blue and green areas correspond to concrete, air and insulation, respectively.

A sketch of a cross section of the ACS model is presented in Figure 4a) and the reduced model for use with Apache in Figure 4b). The depth of the concrete corresponds to the depth of the zone of effective thermal admittance of the ACS, which is 150mm, as estimated in [3]. The thermal properties of the concrete in the reduced model are matched with the ones of the experimental prototype. An important parameter controlling the heat transfer to the concrete slab is the surface heat transfer coefficient between the air and the concrete slab and needs to be specified as a parameter in Apache. The heat transfer coefficient depends on the flow rate and a series of 6 CFD simulations for flow rates ranging from 10 l/s to 240 l/s were run with real weather data.

In Apache, the heat transferred to a wall (Q [W]) is given by

$$Q = h_c \left(T_b - T_s\right),$$

where h_c ([W/m^{2}K), T_b [C] and T_s [C] are the heat transfer coefficient, bulk room and surface temperature. An energy balance of the ACS gives the following relation:

$$A h_c \left(T_s - T_b\right) = \dot{m} c_p \left(T_{in} - T_{out}\right),$$

where A [m^2], T_{in} [C], T_{out} [C], $\dot{m}$ [kg/s] and c_p [J/kgK] are the surface area, inlet temperature, outlet temperature, mass flow rate and heat capacity of the air. We can therefore compute h_c as:

$$h_c = \xi \frac{\dot{m} c_p}{A}, \text{ where } \xi = \frac{T_{in} - T_{out}}{T_s - T_b}.$$

T_{in} , T_{out} , T_b and T_s are found by appropriate averaging from CFD simulations of the ACS at selected $\dot{m}$. By minimizing the residual R:

$$R = \left(\sum_{i=1}^{n} \left(\left(T_{in,i} - T_{out,i} \right) - \xi \left(T_{s,i} - T_{b,i} \right) \right)^2 \right)^{\frac{1}{2}},$$

where the index i runs over the time series for T_{in} , T_{out} , T_b and T_s obtained from the CFD model a value for ξ is found that best satisfies $\xi = \frac{T_{in} - T_{out}}{T_s - T_b}$. The value of ξ minimizing R satisfies $\left(R^2(\xi) \right)' = 0$ and is:

$$\xi = \frac{\sum_{i=1}^{n} \left(T_{in,i} - T_{out,i} \right)\left(T_{s,i} - T_{b,i} \right)}{\sum_{i=1}^{n} \left(T_{s,i} - T_{b,i} \right)^2}$$

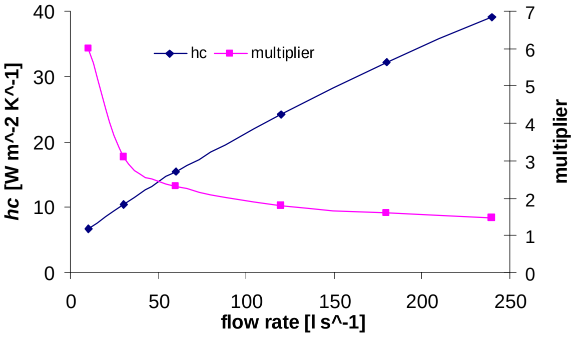

Figure 5 The multiplier ξ and heat transfer coefficient h_c for different flow rates.

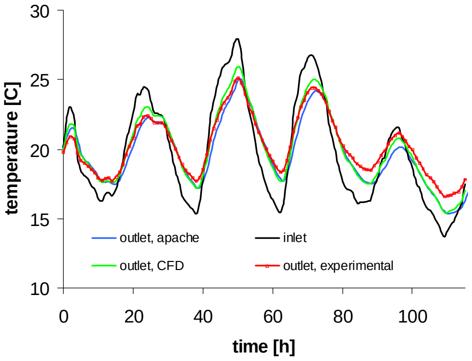

Figure 6 *Comparison between predictions for a single room model of ACS from Apache, experimental and CFD data. The flow rate is 120l/s.*

This procedure applied to flow rates ranging from 10 l/s to 240 l/s gives values for the multiplier ξ as shown in Figure 5. The heat transfer coefficient h_c is finally obtained by substituting $\dot{m}$, c_p and A into $h_c = \xi \frac{\dot{m} c_p}{A}$ and is presented in Figure 5.

IES Apache Model development and validation

The validity of the reduced model has been checked by comparison with results from the full scale physical and the CFD models. In the physical test, ambient air has been passed through the ACS at a fixed flow rate and the air temperature at the outlet has been monitored. Figure 6 shows the inlet (ambient) temperature and compares the temperature at the outlet of the ACS from the physical experiment, from the CFD and IES Apache models. It could be seen that the results from the reduced model compare very well with the ones from the experiment and CFD. Therefore the reduced model could reliably be used to further assess the performance of ACS under realistic conditions.

TRNSYS Model development and validation

TRNSYS is a zone model for building simulation, in which the building is represented by interconnected modules. TRNSYS offers a special type for the simulation of water or air flow through building components. Generally, TRNSYS is working with a transfer function for describing the thermal behaviour of walls and other planar components. For thermally activated building components a special type was developed using a limited two-dimensional, rectangular Finite Differences Model (maximum number of elements: 100). A representative section of the deck system has to be transformed into simplified mesh as shown in Figure 7 for the ACS.

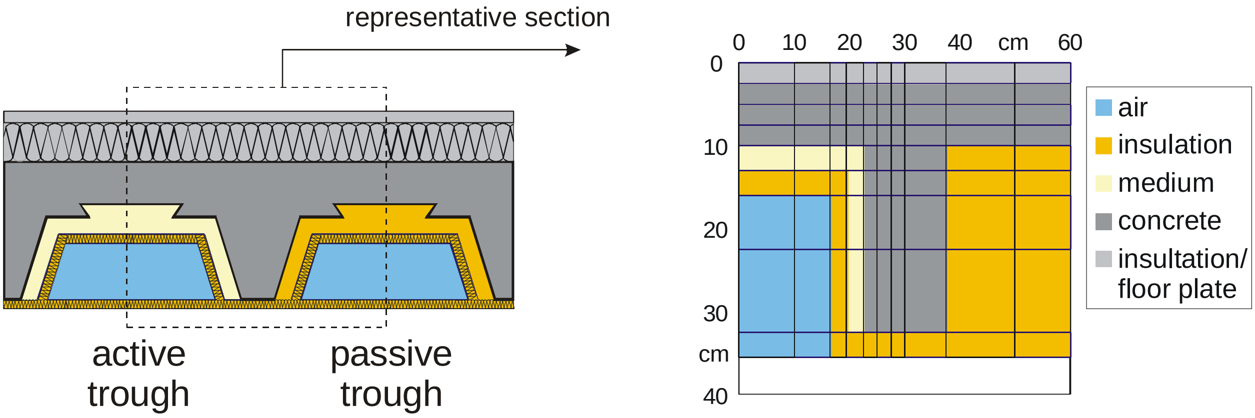

Figure 7 Development for reference section for TRNSYS Type 160 / 360

Based on this reference section the whole active deck element can be described (see Figure 8): In flow direction a partitioning into a number of equivalent sections is assumed (here: 6 partitions, each 2 m). Within a partition a logarithmic development of the medium temperature is considered. To get the full width of the deck element, a sufficient number of reference sections has to be assembled in parallel (here: 6 reference sections).

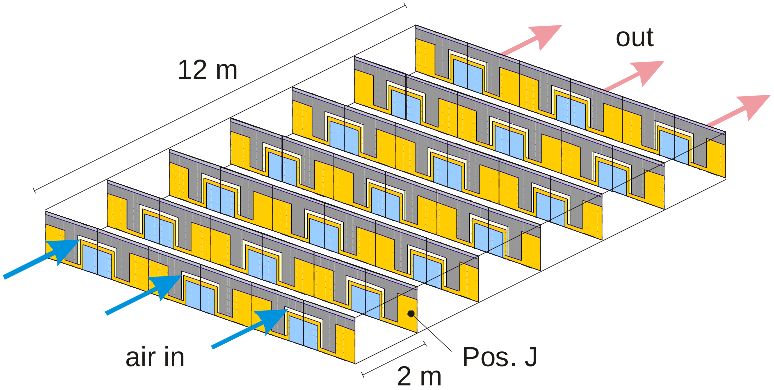

Figure 8 Expansion to a deck element

For the Validation of this numerical model measured data from [1] were taken. This measured data contain the temperature depending on the time (after switching the fans on) and over the length of the deck element. Figure 9 shows, that in the first minutes after forcing the ventilation there is a deviation between measured and calculated air temperatures, but after approximately 1 h the calculations fit very well with the measured values. Figure 10 shows the temperature over the length of the panel, the good correlation (after run time of two hours) is obvious.

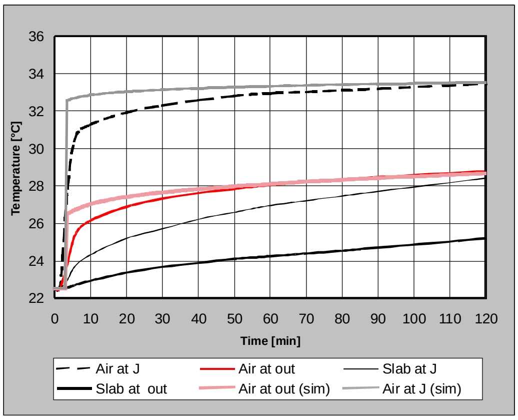

Figure 9 Switching on the panel, comparison of measured and calculated results

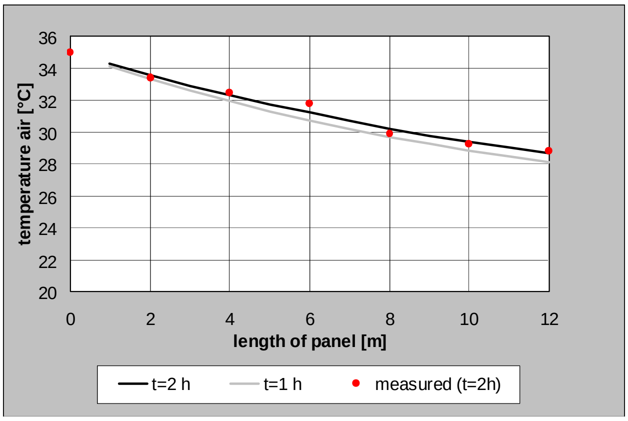

Figure 10 Development of temperature along the panel, comparison of measured and calculated results

RESULTS

The validated numerical models were used to simulate a whole office building, which is illustrated in Figure 11 and has been designed as a part of the EEBIS project [1]. The building has 4 storeys, the façades are oriented north and south, where the south façade is a transparent double façade. This building concept was investigated with the climatic data of Kew, UK, 1994.

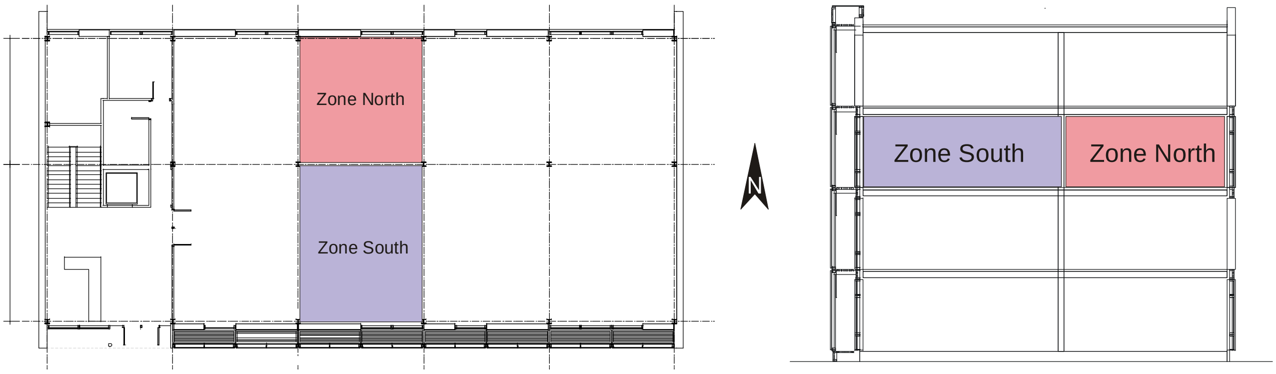

Figure 11 Office building with air cooled slab, ground plan and section plan

Figure 12 shows a comparison of the room temperatures (computed with the Apache and TRNSYS models) for the south oriented part of the third storey of the building. A hot period of the weather data was chosen in order to show the effect of the ACS. In the morning, the room temperature increases as in a conventional building. At noon the room temperature decreases due to the ACS being activated - pre-cooled air is entrained into the room. In the afternoon the air temperature rises again, but not as much as in a conventional building. Parallel calculations without ACS show, that the maximum temperature can be reduced about 4 K. At night, the cool ambient air is used to refresh the "coolth" storage of the ACS system.

This work shows mainly two results:

a) relatively lightweight composite deck systems can be used as an efficient passive cooling system,

b) two different simulation tools, which were calibrated against measured values agree very closely.

The efficiency of the Air-cooled slab is shown in comparison to a conventional, non-air-conditioned building. Using a climate of south England, the maximum room temperature can be reduced by about 4 K. Also in combination with an air-conditioning, the results are interesting: the cooling demand (net energy) can be reduced from 10.1 to 2.8 kWh/m²a (set temperature cooling: 26 °C). The good correlation of Apache and TRNSYS results is evident, the differences are below 0.5 K for this investigated period. This shows that under similar assumptions both tools give similar results and could be reliably used to study similar problems.

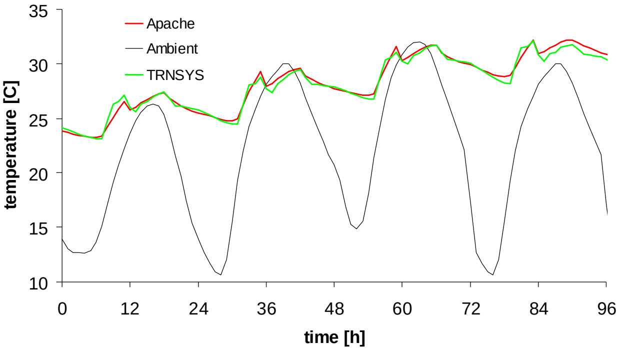

Figure 12 Comparison between predictions from TRNSYS and Apache.

DISCUSSION

Composite deep deck systems, which are the basis for the air cooled slab discussed in this paper, are generally not suitable for passive night cooling. Due to their shape they often come with a false ceiling and the thermal inertia has no contact to the room. The concept of forced air cooling of this deck system changes the situation: The mass of the slab can be efficiently used, the maximum room temperatures are similar to an exposed conventional concrete slab. Additionally the room temperature can be controlled, the surface temperature does not reach unwanted low values and an energy efficient combination with an air conditioning system is possible.

A disadvantage is the need for ducts, flaps and fans to run and control this system. In a further step the energy demand for conveying the air and the control system has to be taken into account. Regarding the investment costs it will be most interesting, if an airconditing system can be removed.

ACKNOWLEDGEMENT

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