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MODELLING OF FABRIC ENERGY STORAGE SYSTEMS – A REVIEW

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ABSTRACT
Fabric energy storage (FES) systems have gained in popularity in the recent years in response to the demand for energy efficient buildings. The dynamic heat transfer mechanisms of an FES require specialised techniques to predict its thermal performance. This requirement has been one of the barriers to the wider use of FES systems. Based on the research literature, this paper presents a critical review of the published mathematical models of FES systems. The paper discusses the usefulness of these models based on the following criteria: the inputs required; the accuracy of predictions; the ability to link with commercially available simulation software; and the degree of difficulty in using the models. The review found that the currently available mathematical models are either not able to predict the thermal behaviour of a building space with an FES system reliably or the models are too complicated and/or require too much specialised knowledge to make them useful.

INTRODUCTION
Increasing energy costs and growing concerns over the environmental impact of human development are adding a new dimension to the never-ending challenge of building practitioners to provide comfortable spaces for building users. The use of conventional energy-intensive air-conditioning systems has been identified as one of the prime targets to reduce the energy consumption and the resulting greenhouse gas emissions associated with the operation of buildings.

For areas with night-times temperatures below 21°C, the combination of high thermal mass and nocturnal ventilative cooling is a viable alternative to conventional air-conditioning (Givoni 1994). This type of building-integrated space conditioning system is variously known as fabric energy storage (FES), thermally active building component system (TABS) or a thermo-active core system (TACS). In this paper, the name FES is used for consistency.

In order to predict the performance and therefore the contribution that an FES might make in any particular type of building or climate, a variety of mathematical models of FES systems have been developed. This paper discusses the usefulness of these models to building practitioners based on the following criteria: the inputs required; the accuracy of their predictions; the ability to link with commercially available simulation software; and the degree of difficulty in using the models.

FES SYSTEMS
A broad range of space conditioning systems integrated into building design can be classified as FES systems. de Sautiles (2005) provides a comprehensive list of FES systems and their operating principles. At its simplest, any building with thermal mass, usually a concrete slab or masonry walls, that can be exposed to nighttime cool ambient air, either by natural or forced ventilation, can be regarded as having a passive FES system.

More complex active advanced FES (AFES) systems have embedded ducts in their high thermal mass components. The heat transfer fluid, usually water or air, is circulated within the ducts to moderate the temperature of the thermal mass. An advanced FES enables the building operator to have more control over the internal environment. These FES usually operate with a mixed-mode or hybrid ventilation systems.

Two of the commercially available FES systems are discussed below as examples:

TermoDeck™
TermoDeck™ (TPCL 2006a) system is one of the most well-known FES systems and uses hollow cores in precast concrete slabs as ventilation ducts (Figure 1). This system was first developed in Sweden in the 1970’s as a fresh air tempering device. The fresh air passes through a number of cores in a serpentine path before entering the space (dashed arrows in Figure 1). It uses the thermal capacitance of the concrete slab to maintain consistent supply air temperature for convective conditioning and the ceiling soffit surface temperature provides radiative cooling.

In the summer, the FES slab is cooled with ambient air at night if the ambient conditions are favourable. The heat collected in the previous day will be dissipated from the heavy structure and the slab will
be able to absorb heat loads produced in the building on the next day. During the day, the warm fresh air is in contact with the cool FES slab which decreases the air temperature. Together with the cool radiative effect from the ceiling soffit, it maintains the indoor temperature within the comfort limits.

In winter, FES slab acts as a heat exchanger to warm the incoming cool ventilation air. The excess heat from daytime internal loads warms up the slab and hence the incoming fresh air. At night, the supply fans are switched off and the stored heat is slowly released back into the space, slowing the decline in internal temperatures. This heat release can reduce the need for early morning preheating of the space.

If the ambient conditions are not favourable, the system can work in conjunction with mechanical heating and cooling systems to provide comfort conditions. Even in conjunction with mechanical conditioning, the system is still able to reduce the peak load and shift the operating hours of the HVAC system to the night-time. This can improves its efficiency and reduces costs by using off peak electricity.

![Figure 1 Typical TermoDeck™ system](image1.png)

![Figure 2 Typical Thermocast™ system](image2.png)

These more complex types of FES system present a considerable challenge to building modelers due to the three-dimensional dynamic energy flow within the FES element and the resulting interaction with the space attached to it. The approaches used, their limitations and the usefulness of the models that have been reported in the literature are reviewed below.

**LITERATURE REVIEW**

A literature survey produced 12 publications describing 13 different models developed in five countries. These models can be divided into three categories.

- Isolated models that predict the thermal behaviour of the FES slab only.
- Stand-alone models that predict the thermal behaviour of the FES slab in addition to one or two spaces connected to the FES slab.
- FES slab models that have been linked to commercially available simulation software.

The studies are presented chronologically.

**Zmeureanu and Fazio (1988)**

These authors studied the thermal behaviour of a room with a hollow core FES system. This model is based on heat balance equations. It is a stand-alone simulation programme to predict the thermal behaviour of the FES slab and the connected spaces.

The model simplified the FES slab as two parallel plates with air passing between them. This model uses the finite difference technique to model a series of nodes which account for the heat transfer through the thickness of the slab and along the airflow path. This model ignores the serpentine airflow pattern, commonly used in many hollow core FES systems.

This model only requires conventional physical data to describe the FES slab and the connected spaces. There is a need to transform the geometry of hollow core slab into the two parallel plates.

This study only analysed the performance of the FES using weather data of one single warm and sunny day in Montreal. As a result, the stability of the model is also unknown since it has only been tested.
in a narrow range of ambient conditions. This model has not been validated against any empirical measurements. Since it is a stand-alone simulation programme, there is opportunity to use it in connection with any commercially available building performance simulation programme.

Beggs et al. (1995)

These authors describe a theoretical study of an air-based hollow core slab system using the finite element method (FEM). The hollow core slab system is a new FES system invented by Beggs et al. (1995). In this FES system, the air passes through channels cast inside a layer of cement sand. This is not an isolated model and predicts the thermal behaviour of the FES slab only.

The authors used a spreadsheet programme to calculate the slab temperature. A shortcoming of the programme is the large element size of 1 m × 1 m. The problem is that the model assumes a uniform temperature for the slab and the structural slab. Furthermore, the procedure that the model uses to calculate the air temperature is questionable. It first calculates the air temperature as if it passes through the slab only and then calculates the slab temperature as if it only passes through the slab. Finally, two sets of results were interpolated to give a resulting air temperature for a 1 m × 1 m element. As a result there is no direct heat conduction between the slab and the slab. No experiments were performed as there was no prototype of such a system being constructed. Therefore, the results were not validated.

Winwood et al. (1997a; 1997b)

These authors established two related mathematical models for a commercially available hollow core slab based FES system (TermoDeck™). The main focuses of these studies are to predict the outdoor air temperature and bulk slab temperature. The first model is a computational fluid dynamics (CFD) model in the commercial CFD package, PHOENICS (1991). This model only predicts the thermal behaviour of the FES slab.

The hollow-core slabs are modelled as rectangular shapes due to the restrictions of the PHOENICS software in the 1990s. Another major limitation in this study is that the ventilation air is modelled with constant physical properties (e.g. density) regardless of temperature and pressure changes along the air path. Moreover, this model also requires the surface temperature adjacent to occupied spaces as an input parameter. Therefore, the usefulness of this model in an occupied space analysis is uncertain, because the accuracy of the model relies on the predicted surface temperature from a previous simulation.

The model has been validated against the UK's Building Research Establishment's measurements published by Willis and Wilkins (1993). There is only a 3% difference between the CFD results and the measurements. This model, however, requires expertise in the use of a CFD package and it requires considerable computational power to simulate the behaviour of the FES slab.

In order to improve the useability of results, the authors defined a new coefficient called storage efficiency. This coefficient is derived from their CFD study results to replace a number of poorly defined input variables, such as the overall heat transfer coefficient of a FES slab. Unfortunately, each variation in FES slab configuration requires a new CFD analysis to obtain the storage efficiency factor.

The second model is a "multi-node model", as defined by the authors. This is essentially a one-dimensional lumped parameter model. This model uses the storage efficiency coefficient, either from the previous CFD analysis or from an analytical equation that requires a known average heat transfer coefficient for the FES slab (Winwood et al. 1997b). This model has been linked into a general building performance simulation software, ESP-r (ESRU 2002). The applicability of this model depends on the availability of storage efficiency coefficient of the FES system design. It also requires some modification of the ESP-r programme to be able to input the storage efficiency coefficient of the FES slab. However, this should not be a major concern as it is a one-off modification of the software package. There is an average variation of 1.6% and 2.4% between the BREF measurements and predictions of room and slab temperature respectively.

Ren and Wright (1998)

These authors developed a stand-alone star RC-network model to study the thermal behaviour of an office space with two hollow core FES slabs, one as the ceiling and the other as the floor. The FES system being studied is a three-pass TermoDeck™ system. In this arrangement, the supply air passes through three of the five hollow cores in the FES slab. In this RC-network model, the slabs are modelled in two separate portions to account for the different rates of heat transfer. The top half is coupled to the space above as the floor, and the bottom half is coupled to the space below. Heat conduction from one side of the slab to the other side is ignored in this model. The authors justify this assumption because the slab temperature is principally determined by the temperature difference between the ventilation air and coupled spaces. By nature, this is a lumped parameter model, and only an average (core) air temperature is predicted.

The lumped model uses a simplified geometry to approximate the actual slab thermal capacitance and thermal resistance. Predictions of space temperature by this model had a maximum deviation from test
cell measurements of 24% (4.2°C) under a low velocity air supply. By contrast, the deviation from test cell measurements of space temperature was reduced to 5% (0.9°C) with a high air supply velocity.

This model has been validated against controlled measurements from a test room located inside a large hall. As a result, the test room is not subject to direct solar radiation. Moreover, the test was only conducted for artificially created cyclic ambient conditions. These limitations significantly reduce the usefulness of the results. A major portion of the cooling effect of the FES system is from the radiative heat exchange between the FES slab and the surrounding surfaces and occupants. The validity of the surfaces temperature in the test space may not be realistic due to the omission of direct solar gain in the space.

**Fort (1999)**

This author developed a finite difference model (FDM) to be integrated into the building performance simulation software, TRNSYS (Klein et al. 2005), and can be used in conjunction with its TYPE 56 building sub-routine.

In this model, the programme calculates a series of two-dimensional cross-sections of heat balance and then integrates them to solve the three-dimensional heat transfer.

This model reduces the computational requirement by assuming zero heat transfer across cores and hence creates a ‘symmetric boundary’ between the cores. The hollow core slab can then be represented by a number of repeated sections and these sections are divided into nodes. The heat balance is solved using the FDM. The density and heat capacity of the ventilation air is assumed to be constant regardless of the temperature and pressure inside the FES slab. Therefore, the dynamic properties of the ventilation air are ignored in this model, the expected average values are used instead.

Several flaws in this model are identified as follows:

This model treats the FES slab as a series of straight long concrete air ducts, and hence the changes in air path direction at the connections between cores have been neglected. These sections are reported to have a significantly higher heat transfer coefficient (Barton et al. 2002). Weber and Johannesson (2005) commented that this model has the disadvantages of:

a) being restricted to rectangular geometry, b) the need for a relatively small time step of 10-15 minutes to maintain its stability and c) sensitivity to the number of elements and their size. Hence a sensitivity analysis or highly experienced software operator is needed to produce reliable predictions.

The inaccuracy resulting from the assumption of zero heat transfer between cores is amplified when the length of FES slab increases and the supplied air temperature is significantly different from the room temperature. The definition of parameter “roughness” is unclear. The roughness of the internal duct surface can significantly influence the air flow pattern inside the FES slab, and hence varies the heat transfer rate.

This model does not provide the opportunity to vary the properties of the slab material (generally concrete). The recent trend to use high density and strength concrete highlights this shortcoming. The model also precludes the use of FES performance-enhancing techniques such as adding metal powders to the concrete to increase the thermal conductivity, and hence its thermal responsiveness.

**Koschenz and Dorer (1999)**

These authors studied the performance of a hydronic concrete core system. This model was later integrated into the TRNSYS Type 56 sub-routine as the wall with an active layer. This model is an analytical solution to the behaviour of heat transfer between the embedded water pipes and the occupied space through the concrete slab. This model has a limit on the pipe diameter to pipe spacing ratio of 0.2 (d/dp), as shown in Figure 3.

![Figure 3 Wall with an active layer for floor heating or cooling (Klein et al. 2005)](image)

Therefore, it is not applicable to predict the thermal performance of a hollow core ventilation FES system, as the diameter of the hollow core is usually larger compared to the core spacing. This model has not been validated against experimental results. The predictions from this model have only been verified by comparison with a finite element model, and no details are provided.

**Barton et al. (2002)**

These authors studied the ‘TermoDeck’ hollow core slab system using a two-dimensional explicit FDM. Their model takes account of the heat transfer along the cores and vertically across the thickness of the slab. The third dimension, i.e. between cores, is ignored by the authors as the temperature difference between cores, and hence heat transfer across cores, is assumed to be minimal. This is an isolated model.
to predict only the thermal behaviour of a FES slab. It is not linked to any building prediction software.

The model studies the thermal behaviour of the hollow core slab with a cyclic 24-hour sinusoidal air temperature distribution. Outside air temperature and the room condition are given as the boundary conditions to the model. As a result, the model only includes half the slab thickness as the authors assumed that the boundary conditions are identical on both sides of the slab.

This model has been developed in the spreadsheet programme, EXCEL, which restricts the opportunity to integrate it with other simulation programmes. This model has been validated against published data by Willis and Wilkins (1993) with an accuracy of 0.2°C for the outlet air temperature and 0.65°C on the core air temperature range. However, the results should be interpreted with caution because this model requires both the room temperature and the indoor peak temperature time-lag (constant two hour phase shift) as model inputs. Therefore the two major variables that need to be predicted are required as inputs.

Weber et al. (2005)

These authors established two mathematical models for water-based FES systems. The system modelled is a concrete slab with embedded plastic pipes circulating chilled or hot water. The first model is a FEM model with a two-dimensional cross section along the water pipe. The predictions from this model achieved a maximum discrepancy of 0.5°C compared to measured data (Weber et al. 2005).

The second model is an improved RC star-network to estimate the heat balance of the slab. This model is written as a calculation module linked to the simulation programme, TRNSYS. It is reported that the predictions of slab temperature have a maximum discrepancy of 0.2°C compared to measured data (Weber et al. 2005).

These two models ignore the serpentine arrangement of the embedded water pipes. This is because the authors consider that the heat exchange between the pipes should be negligible due to the high heat capacity of the concrete. A heavy raised floor structure is also included in both mathematical models of the FES concrete slab. This decision was made because the measurements show a significant phase delay of seven hours between the peak temperature of the top surface of the concrete slab and the underside of the raised floor. The thermal capacitance of the heavy raised floor plays an important role in the dynamic heat transfer from the activated floor heating and/or cooling system to the occupied space. The inclusion of such a raised floor structure has limited the model’s transferability to a different design, as the raised floor becomes an inseparable component in the calculation module.

In another publication, Weber and Johannesson (2005) developed a refined RC-network model to predict the behaviour of water-based FES systems. The model is a refinement of the star RC-network from their previous study (Weber et al. 2005).

![Figure 4 Modified triangular RC-network denoted Δ-G network (Weber & Johannesson 2005)](image)

This model is the triangular RC-network (Figure 4), which uses not one but two parallel sets of thermal resistance and thermal capacitances (RC link) to determine the heat flow between the nodes. While the results from this study shows that this RC-network can be incorporated into general building performance simulation software such as TRNSYS and IDA (EQUA 1999), significant effort is required to "optimise" the RC-network for any change in the system construction. This is because the RC link is not only determined by the physical properties of the construction but also has to 'match' the results from an FEM study (Schmidt & Johannesson 2004). As a result, this method has a two-step procedure for altering the design of the FES slab. First, a FEM simulation has to be conducted in order to provide inputs to optimise the triangular RC-network. After this step, the optimised triangular RC-network can be used in conjunction with building simulation software.

Karlstrom (2005)

This author developed an FEM model for the TermoDeck™ system in numerical analysis software FEMLab™ (COMSOL 2005). In a Masters Degree thesis, the author describes the refinement process of his FEM model from a simple steady-state two
dimensional FEM model to a transient three-dimensional model incorporating CFD capability. However, the descriptions of his FEM model are not adequate and there is no detail provided of the validation process of the model.

**Fuller and Cheung (2005)**

These authors studied the long-term energy performance of a generic hollow core FES system in various Australian climates. The results of a matrix of combinations of three slab sizes, three supply air change rates and four control strategies in six capital cities in Australia are presented. This is the only publication that has studied the long-term energy performance of an FES system. It is also the only study conducted outside mid-northern Europe and North America.

![Figure 5 Schematic diagram of the Fuller and Cheung model](image)

In this study, the authors ignored the serpentine flow of the supply air to minimise the complexity of the operation. The model, however, is capable of modelling such a configuration, but doing so would result in a loss of simplicity. Another shortcoming of the model is the lack of validation against experimental measurements. The accuracy of this model is not discussed in their paper.

<table>
<thead>
<tr>
<th>Key</th>
<th>Mathematical methodology</th>
<th>Degree of validation</th>
<th>Connection to simulation package</th>
<th>Usability for Practitioners</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP – Distributed Parameter</td>
<td>DP</td>
<td>L</td>
<td>N</td>
<td>L</td>
</tr>
<tr>
<td>LP – Lumpred Parameter</td>
<td>DP</td>
<td>NA</td>
<td>N</td>
<td>L</td>
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<tr>
<td>A – Analytical</td>
<td>LP</td>
<td>SE</td>
<td>L</td>
<td>C</td>
</tr>
<tr>
<td>L – Limited</td>
<td>DP</td>
<td>SE</td>
<td>L</td>
<td>C</td>
</tr>
<tr>
<td>NA – Not Available</td>
<td>DP</td>
<td>SE</td>
<td>N</td>
<td>L</td>
</tr>
<tr>
<td>SE – Short term Empirical</td>
<td>DP</td>
<td>SE</td>
<td>N</td>
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<tr>
<td>Y – Yes</td>
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<tr>
<td>N – No</td>
<td>DP</td>
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<td>C – Conditional</td>
<td>DP</td>
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<td>H – High</td>
<td>DP</td>
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**MODEL COMPARISON**

Ideally all the models would have been obtained and perform a comparative study of their predictions. It is unlikely that all these models can be obtained, since only two of the models are publicly available. Furthermore, the wide spectrum of software expertise required to operate all these models prohibited such a comparative study. Table 1 provides a summary of four characteristics of the models reviewed, namely: mathematical methodology, degree of validation, connection to simulation package and usability for practitioners.

**CONCLUSIONS**

The studies reviewed were mainly conducted in four countries in mild to northern Europe, the exceptions being the first published study by Zmeureanu and Fazio (1988) in Canada and the last study by Fuller and Cheung (2005). The ability of models developed in the cool temperate and cold climates to predict the performance of FES systems applications in warmer climate is not proven. Moreover, most of the studies...
only investigated FES behaviour over a relatively short period of time where the memory effects of the FES system may not have been adequately allowed for.

The models reviewed can be separated by their mathematical methodologies. The first group can be described as the distributed parameters models, and it includes all the FDM, FEM and CFD models. This group of models provides the highest degree of flexibility to model any changes in FES system design. However, they require high level of computational power and expertise. Specialised software is also needed as most of the commercially available general building simulation software does not have the required facilities to run these models. The second group are the RC-network models. They can be easily connected or integrated into general building simulation software. The main weakness of this group of models is their lack of adaptability. Changes in FES configuration cannot be directly translated to an RC network model, because it requires a certain factor that can only be obtained as an output from a distributed parameter model. The third group are analytical models, although there is only one amongst the models reviewed. There is a consensus in the literature that there are no analytical solutions for hollow core based FES.

Most of the models reviewed require a certain degree of simplification of the geometry of the FES slabs. There is minimal guidance given on the simplification process, such as the trade-off between volume, surface area and slab thickness. The effect of changing precedence has not been investigated. All of the isolated FES slab models require the slab surface temperature as an input parameter. This requirement discounts the ability of these models to account for the interaction between the FES slab and space to which it is connected. Even though the fluctuation in FES slab surface temperature is expected to be low, this practice essentially treats the FES slab as an air pre-conditioner separated from the space. The RC-network models of Weber and Johannesson (2005) and Winwood et al. (1997b) must obtain key input parameters from a separate model. Therefore, the user has to perform an extra simulation (either in FEM or CFD) and this requires a high level of expertise and computational power.

Only six of the thirteen models in this survey demonstrated any type of linkage to general building simulation software. As discussed above, three require specific inputs that can only be obtained from experimental results or from another high-end model. Only the Fort (1999) model and that of Fuller and Cheung (2005) are able to simulate air-based FES systems without requiring special input parameters.

The literature indicates that there is no validated mathematical model available that can be used with a commercially simulation package, and which is able to predict the thermal behaviour of a hollow core FES system with serpentine flow. The model developed by Koschranz and Dorer (1999) can only be used with small pipe diameters, which means the model is not usable for a hollow core air-based FES system. The RC-network models from Weber and Johannesson (2005) and Winwood et al. (1997b) require a separate model in order to obtain key input parameters. Therefore, the user has to perform an extra simulation (either in FEM or CFD) and as before this requires a high level of expertise and computational power. The model developed by Fort (1999) is considered to be the closest of any of the reviewed models that can be used in this way. However, due to its inability to model a serpentine flow and the required sub-hourly calculation domain, the usefulness of this model for practicing engineers is questioned. The approach of Fuller and Cheung (2005) is promising but requires full validation before it can be considered to be useful for practitioners. The authors believe the validation and further development of the Fuller and Cheung (2005) model on other general building simulation software can assist the uptake of FES systems in building design. This model has the potential to be applied to building simulations without going through the program developers and software marketing stage, effectively bypassing the ‘modeling bottle neck in simulation software’, as described by Sahlin (1996).

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