High-resolution analysis for the development of TABS in lightweight structures

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Abstract

Numerical methods, such as nodal models, are available for the design and control of thermally activated building systems (TABS). In the past, these methods have been successfully developed and applied in the design of traditional heavyweight concrete structures. Further, there has been an increased usage of low supply temperature sources, typically derived from renewable energy. The low supply temperatures require more careful planning to achieve the necessary comfort constraints for modern buildings. This research investigates the applicability of high-resolution analysis, for the design and development of TABS for lightweight concrete structures. In addition to the energy performance of the system, the approach also considers the thermal comfort of the associated conditioned room.

Introduction

According to the International Energy Agency (IEA), a continuation of current construction trends will result in a growth of almost 50% in global energy demand for buildings in the period from 2010 to 2050 (IEA, 2013). The predicted increase can be limited to a growth of 25% with an estimated investment of USD 31 trillion, which can be recovered through energy efficiency improvements (Gouldson et al., 2015).

Currently, in European buildings, space heating is responsible for approximately 75% of operational energy demand, while the structure of a building and the installed HVAC equipment can account for at least 50% of embodied energy (Johra and Heiselberg, 2017). Hence, an approach that simultaneously reduces operational and embodied energy demands would have a significant impact on the overall lifecycle energy demand and the related greenhouse gas (GHG) emissions of a building.

This research investigates a concept of combining a thermal space conditioning system with a lightweight structural floor element, which reduces initial embodied energy. The thermally active building system (TABS) approach addresses many of the constraints resulting from low GHG emissions design, such as providing an efficient method for harnessing a low temperature renewable source. This can be achieved while also maintaining a high standard of occupant thermal comfort (Rhee et al., 2016). However, the combination of a lightweight structure with complex geometry and a low temperature renewable energy system results in a number of challenging design issues. These issues range from thermal loss management (Lydon et al., 2015) to complex system control (Schmelas et al., 2015).

Figure 1: The NEST building (Empa, 2016).

To address the issues outlined, we propose an analysis framework based on computational fluid dynamics (CFD). In previous work, we presented a systems model of a lightweight structural TABS (Lydon et al., 2016). The study included a method for dealing with the complex geometrical and structural constraints associated with lightweight concepts. Further, we detailed the energy analysis of two lightweight structural TABS for a real project on a building-scale and a district-scale (Lydon et al., 2017). In this paper, we supplement the TABS model with a comfort model of the associated conditioned room. In particular, we utilise existing full-scale experimental data (Li et al., 1993) to calibrate the unstructured numerical mesh. We employ a model of a lightweight TABS with simplified geometry to test a modelling approach of combining a system model with a comfort model. The high-resolution analysis framework will be used for the development of TABS for a lightweight structural floor, in terms energy performance and occupant thermal comfort.

Background

This section provides background information relating to the research project, the structural aspects of the lightweight floor and the building energy systems integration.

NEST HiLo

NEST (Figure 1) is a district scale project by Empa (Swiss Federal Laboratories for Materials Science and Technology), to demonstrate innovation in the built environment. NEST (Next Evolution in Sustainable

https://doi.org/10.26868/25222708.2017.116

Figure 2: Exterior rendering of the HiLo building (HiLo, 2016).

Building Technologies) provides a building infrastructure and access to an advanced thermal and electrical energy systems. Up to fifteen modular buildings can be added to the NEST backbone (Empa, 2016). NEST serves as an interactive demonstration and research facility for the design of sustainable buildings and districts. The construction of the NEST building and the energy systems was completed in 2016.

As one of the first NEST modular buildings, HiLo will be a two-bedroom apartment and will be used to exhibit innovation in the domains of building energy systems and structural design. The HiLo (High performance, Low energy) project will investigate integrated design methods that reduce embodied and operational energy. HiLo (Figure 2) will be a net plus energy building in operation phase (Lydon et al., 2017) and will begin construction in 2018. The work presented in this paper is related to a lightweight concrete element with integrated building systems that is being developed for the project (Figure 3).

Lightweight funicular floor system

The Block Research Group of ETH Zurich has developed the lightweight funicular floor system. The floor system is a thin concrete element, consisting of a vault and stiffening fins. The design is related to a form-finding Trust Network Analysis method that provides a high degree of control over the vault shape (Block, 2009). The funicular shape of the vault delivers mainly compressive stresses. The tension forces are resolved at the edge of the structure with tension ties (Liew et al., 2017). The structural system is developed to reduce the concrete thickness to approximately 20 mm for the vault and the fins. Therefore, the funicular floor uses considerably less concrete than traditional heavyweight structures (López López et al., 2014).

Thermally activated building systems

TABS are a feasible method of transferring building space heating and cooling supply to renewable energy sources. This conversion to low exergy methods (Schlueter and Thesseling, 2009) can be achieved using existing materials and construction technology.

TABS increase the temperature of large active surfaces of an internal zone. Mainly through radiative heat transfer, the surface temperature of non-active surfaces are also increased. This results in an overall increase in the radiant temperature of the internal zone. This can provide a stable operative temperature with an air temperature of approximately 2 °C lower than traditional air based systems (Hao et al., 2007).

To fully exploit the benefits of TABS, an understanding of the thermal dynamics of the internal zone is required. This relates to the interaction of the TABS with the zone thermal mass and in some cases the building furniture and interior fixtures (Raftery et al., 2015). This is especially important when TABS are employed in lightweight structures using a low supply temperature. Further, TABS are typically dependent on a companion ventilation system to manage CO_2 levels in the winter period. While in the summer period, some strategies provide for a cooling of the thermal mass of the TABS panel using mixed night ventilation. Therefore, a high-resolution analysis approach that provides detailed information on the interaction of TABS with internal building mass and ventilation would improve active and passive control strategies.

Methods

Current design methods for TABS involve three main steps: performance analysis of the panel (System model),

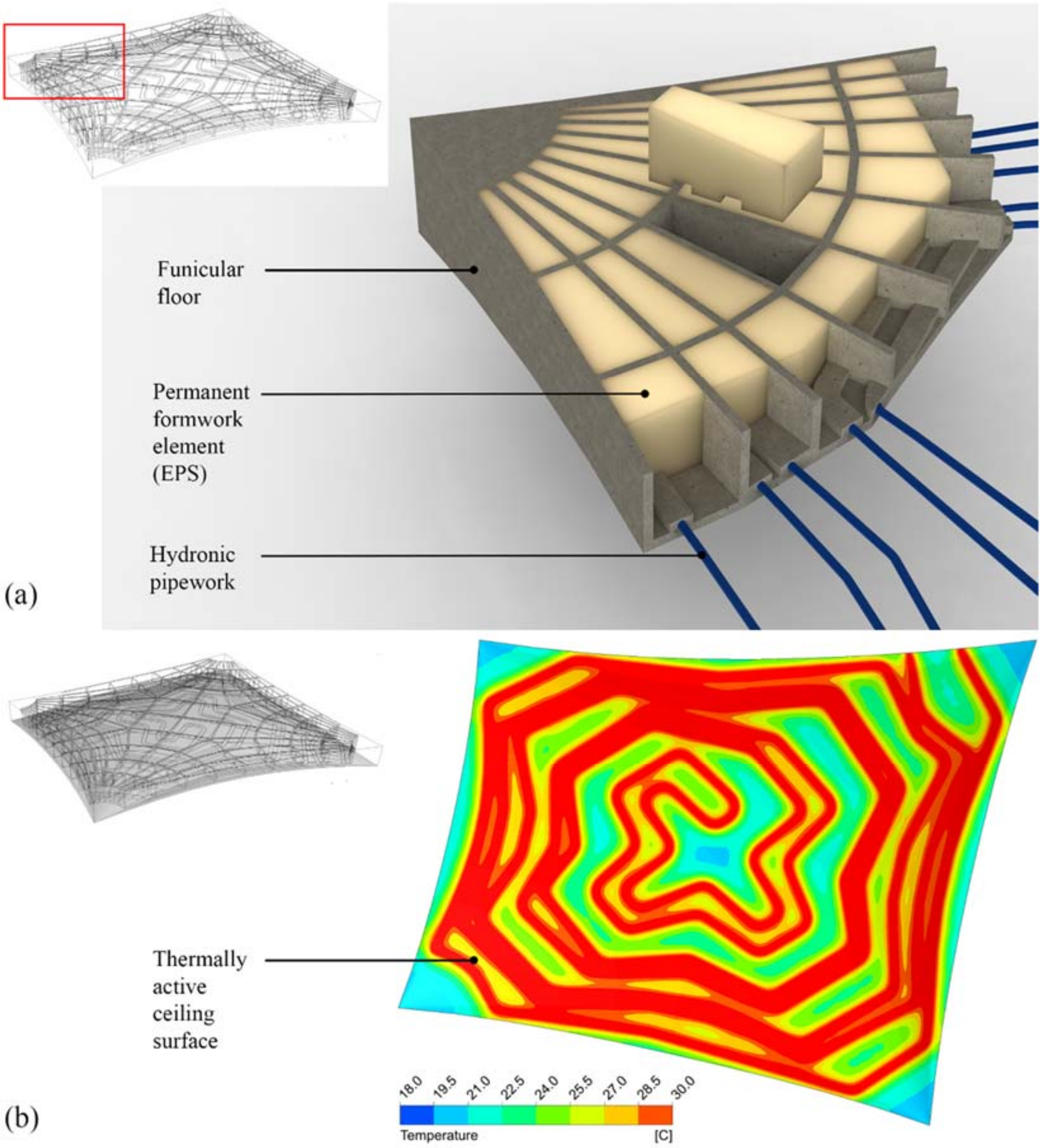


Figure 3: (a) Exploded view of the funicular floor integrated with a hydronic pipework system (b) Temperature contour plot of the ceiling surface.

estimating the building thermal loading (Energy evaluation) and selecting a control method (Control model):

1. The radiant panel (system model) is typically modelled using resistance/capacitor nodal elements for each material layer.
2. The Unknown-But-Bounded (UBB) method (Lehmann et al., 2011) can be used to characterise the influence of the solar and internal thermal gains of the building using a dynamic nodal model. This approach includes additional thermal mass located in each zone.
3. Control can be applied with a basic outside temperature compensated supply-water temperature method. This can be improved by using the pulse width modulation method (PWM) (Lehmann et al., 2011), applied with an intermittent use profile to the circulation pump, which improves efficiency.

These numerical methods have been mainly developed for use with traditional heavyweight concrete structures at higher temperatures. Typically, higher temperature systems have quicker reaction time in terms of modifying internal conditions. Due to thermal comfort requirements, low temperature systems will require advanced control algorithms. Therefore, it is proposed to replace the nodal model of Step 1 with a high-resolution method (Finite element or computational fluid dynamics (CFD) with conjugate effects) and provide an additional Step 2b (Comfort Model) to assess the impact of the selected control method on the comfort of the occupants at transitional periods (Figure 4).

High-resolution methods fully resolve the thermal behaviour of the panel, which is important due to the thinness of the structural element. This includes an estimate of the steady state performance (Figure 3b) and the panel reaction time using transient simulations.

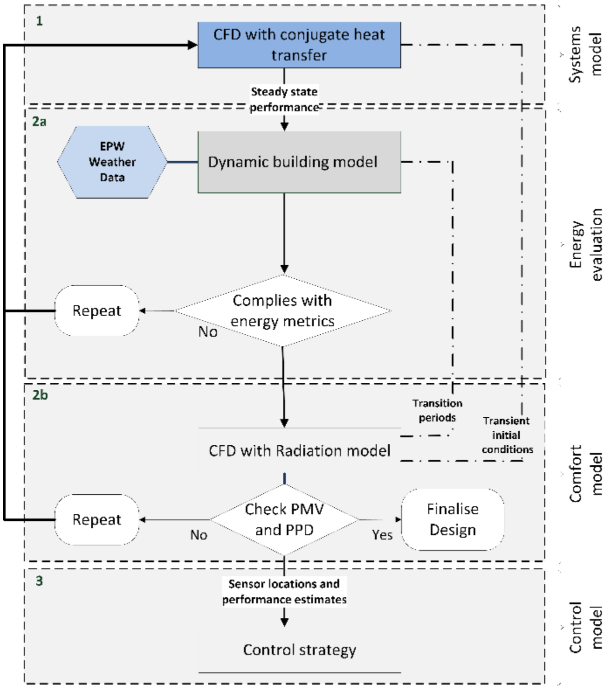


Figure 4: Proposed modelling framework for TABS in lightweight structures.

The results from Step 1 can be used to inform the dynamic building model (DBM) and in turn complete the energy compliance metric for the design phase.

The additional Step 2b is provided to assess the impact of the selected control method on the comfort of the occupants at transitional periods. These are periods when the building systems are changing between heating and cooling modes of operation. In previous work, a DBM model has been strongly linked with a CFD model (Beausoleil-Morrison, 2002). We use a similar approach, in which the BMS is used to identify problem periods for the TABS control system. The DBM data, such as external temperature and surface heat transfer coefficients are then used to initialise the CFD model. This model is implemented using CFD with a radiation model over short time periods. In order to manage the computational resource, the Step 1 model informs the surface temperature of the radiant surface.

Literature review

A two-dimensional numerical model was used to investigate the comfort performance and the energy consumption of a hydronic radiant panel system (Tye-Gingras and Gosselin, 2012). An optimisation study was carried out based on the numerical data of a room with wall and ceiling radiant panels in a residential building. The design variables of the study were panel size, panel location and the fluid inlet temperature. The velocity and temperature field calculation within the room was coupled with the radiant panel calculation. The solution was reached using an iterative process. The results indicate that fluid temperature was the key variable for the simulation.

A numerical study of a three-story building atrium was used to access natural ventilation and thermal comfort (Hussain and Oosthuizen, 2013). The validated CFD model employed the k-omega SST turbulence model and the discrete transfer radiation model (DTRM) with the commercial code Fluent. The study focused on buoyancy-driven natural ventilation during day and night periods. Design curves were used for the initial sizing of the inlets and outlets (Holford and Hurt, 2003). Based on the numerical results, the PMV (predicted mean vote) and the PPD (predicted percentage of dissatisfied) were calculated for a thermal comfort assessment. In terms of thermal comfort, the building performed satisfactorily during working hours. The study also examined a thermal chimney, which was heated by high temperature water circulation (solar collectors) at the wall surface during the night. This process induced natural convection to aid night purging of the air within the atrium.

The Fiala model of human heat transfer and thermal comfort (Fiala et al., 1999) has been coupled with CFD for building applications (Cropper et al., 2010). A case study of a classroom showed that the method provided an improvement in the accuracy of the calculation of body surface temperature and the related buoyancy driven airflow (Cook, 2015). This coupling approach has also been applied in other engineering disciplines, such as the automotive industry.

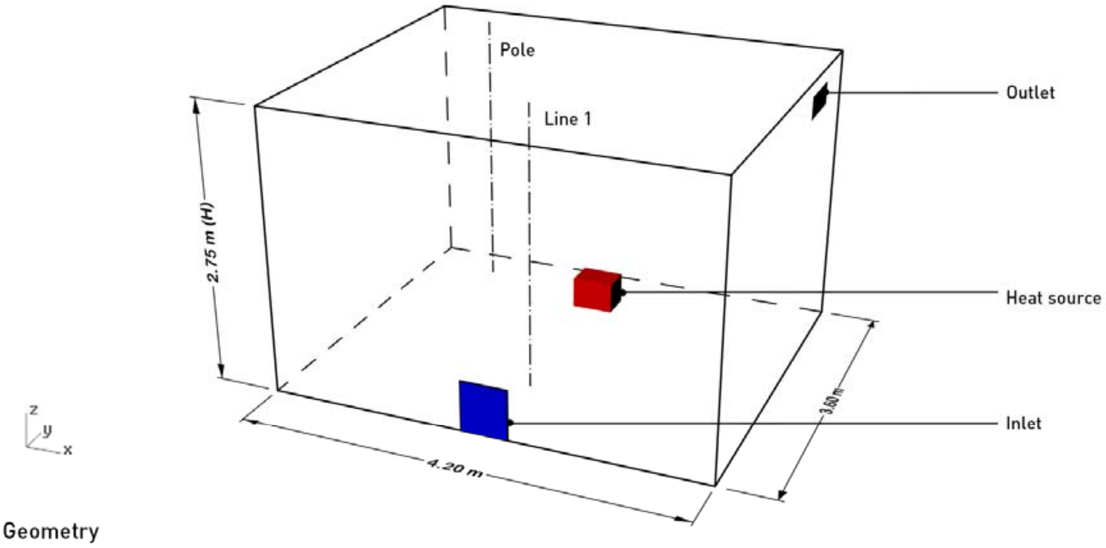
Li et al. carried out a detailed experimental study in relation to radiative heat transfer on room air temperature (Li et al., 1993). The room had a displacement ventilation system and a local heat source. Air temperature was recorded using a set of 30 thermocouples, which were attached to a vertical pole (Figure 5a). In addition, room surface temperature was measured with 22 thermocouple that were distributed over the wall and ceiling. The impact of varying the wall emissivity, heat load, inlet flow rate and inlet temperature was measured over a number of experiments.

Gilani et al. used the results to construct a calibration model for CFD analysis of internal air flow (Gilani et al., 2015). This work provided detailed information on the required grid resolution, turbulence models and discretisation schemes to analyse stratified indoor air with a heat source. The experimental work by Li et al. could also be used to calibrate the modelling of radiative heat transfer in a building zone.

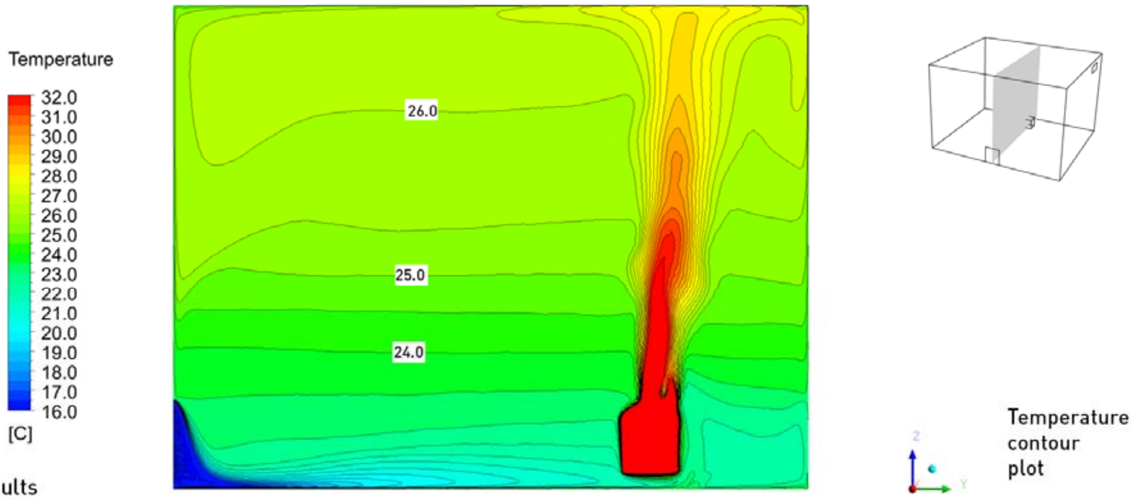
The present study builds on previous research on high-resolution thermal analysis in the context of lightweight structural TABS with an emphasis on digital fabrication.

Calibration

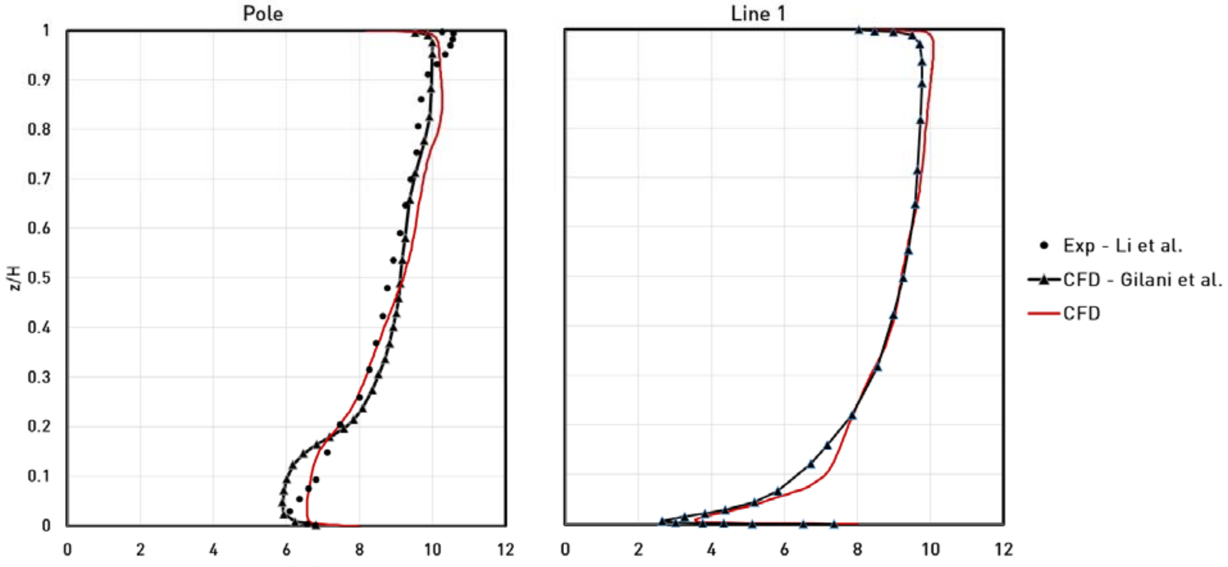
The work described in the previous section by Li et al. and Gilani et al. was used as part of the calibration process for the CFD comfort model. The room layout outlined by Li et al. was used to setup the model geometry (Figure 5a). The CFD model used by Gilani et al. employed a structured mesh with hexahedral cells. As the present research deals with a system with a relatively complex geometry, a tetrahedral and prism cell unstructured mesh was employed. The purpose of the calibration is to identify the mesh and model settings required to capture stratified air characteristics of a building room with a heat source and a ventilation system.



(a) Geometry



(b) Results



(c) Calibration

Figure 5: (a) Geometry based on the experimental room by Li et al. (b) Results from the CFD calibration model (c) Comparison of the experimental and the numerical results.

The model and boundary condition settings were matched to the study by Gilani et al., with the main details summarised here. The heat source was modelled as a solid with a heat generation rate of 8333 W/m^3. Based on experimental measurements, the wall surface temperatures were fixed with a user-defined function. The velocity inlet was set based on a room air change rate of 1 h^{-1}. A setting of zero pressure was used for the boundary condition of the outlet. The mesh had a maximum y* value of 1.7 (y* is a dimensionless distance that is related to the fluid properties and the height of the first mesh cell). Figure 5b shows the results of the calibration model in terms of a central ZY plane temperature plot. Similar to the results of Gilani et al., a thermal plume is formed over the heat source and the air is stratified depending on temperature. Figure 5c shows the results from a vertical pole with a comparison of the experimental measurements by Li et al., the CFD results of Gilani et al. and the CFD results from the present study. Comparing to the experimental measurements, the present CFD results are comparable to the results of Gilani et al. for the pole location.

A further comparison of the CFD cases is shown for a vertical line 1 between the air inlet and the heat source. The present CFD results show a slight over prediction of temperature (pole and line 1) for the upper stratified air layers, which may be related to mesh density.

Simulations

To demonstrate the use of high-resolution analysis for the development of TABS in lightweight structures a model with simplified geometry was employed (Figure 6). The model dimensions were selected to allow testing of the numerical methods and management of the computational resources.

The geometry of the solid domain and the two fluid domains is shown in Figure 7a. The solid domain is composed of a thin concrete element and expanded polystyrene (EPS) insulation. A fluid pipework domain is embedded in the concrete element, which completes the geometry of the systems model.

ANSYS Workbench was used to generate a tetrahedral mesh with up to 10 prism inflation layers at the wall of the fluid domains. The finite volume CFD code ANSYS Fluent 17.0, with the pressure-based solver, was used for all of the numerical simulations. The second order upwind discretisation schemes were used for all of the variables, except for pressure. The comfort model used the PRESTO! discretisation scheme for pressure. Conjugate effects are used to model the heat transfer in the solid domain.

Systems model

The thermal conductivity of concrete was set at 1.85 W/m K and at 0.04 W/m K for EPS insulation. The thermal boundary condition of the ceiling surface and the remaining external surfaces was set with a heat transfer coefficient of 6 W/m^2 K and a free stream temperature of 18 ˚C. The inlet supply temperature of the water inlet of the pipework was set to 31˚C.

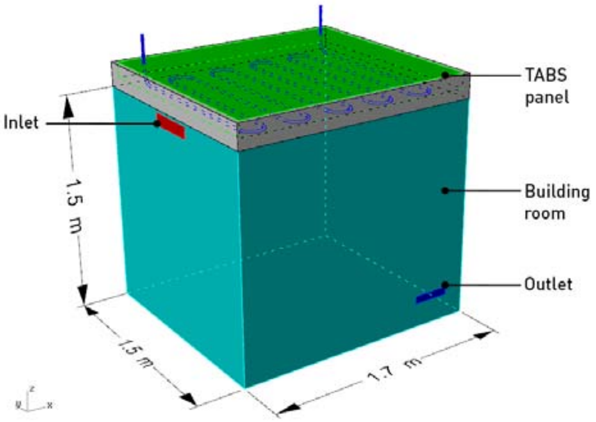


Figure 6: Simplified geometry.

For the systems model, the turbulent component of the fluid flow was modelled using the Realisable k-epsilon turbulence model with scalable wall functions. When the steady state calculation with an active solid and pipework fluid domains had converged, a wall profile for temperature was stored (Figure 7b).

A monitor of average temperature at the ceiling surface was used to track the convergence of the model equations. The simulation was continued until the residuals were less than 10^{-3} and the surface monitor showed no significant change over 50 iterations.

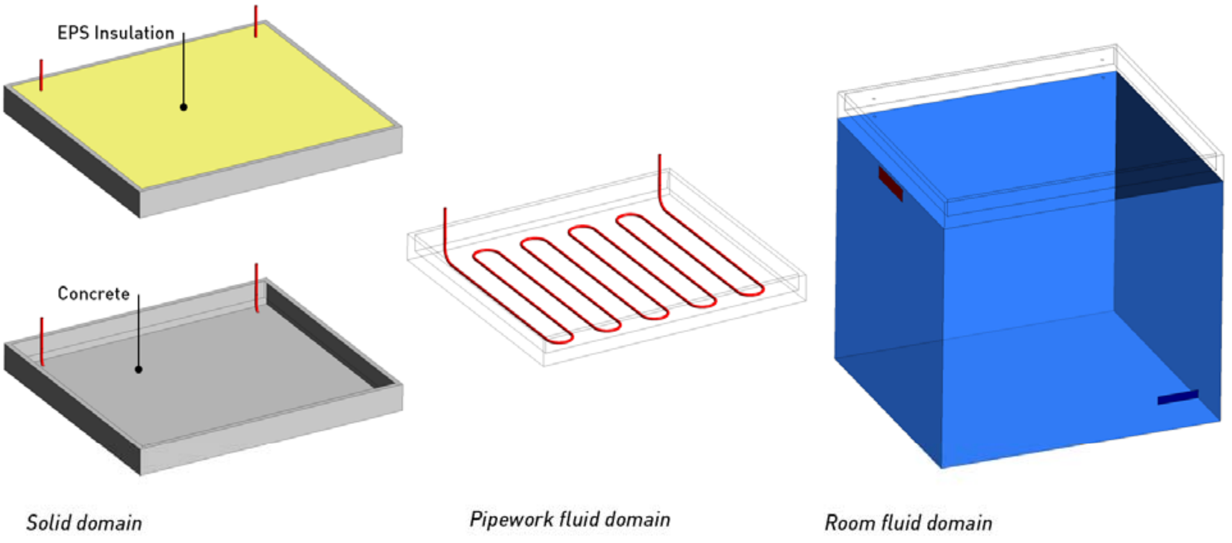
The pipework fluid domain was deactivated by suppressing the pipework mesh. The wall temperature profile was applied to the solid domain. Using ten-second time steps, the transient behaviour of the systems model was estimated (Figure 7b). This approach reduces the computational overhead for the analysis.

Comfort model

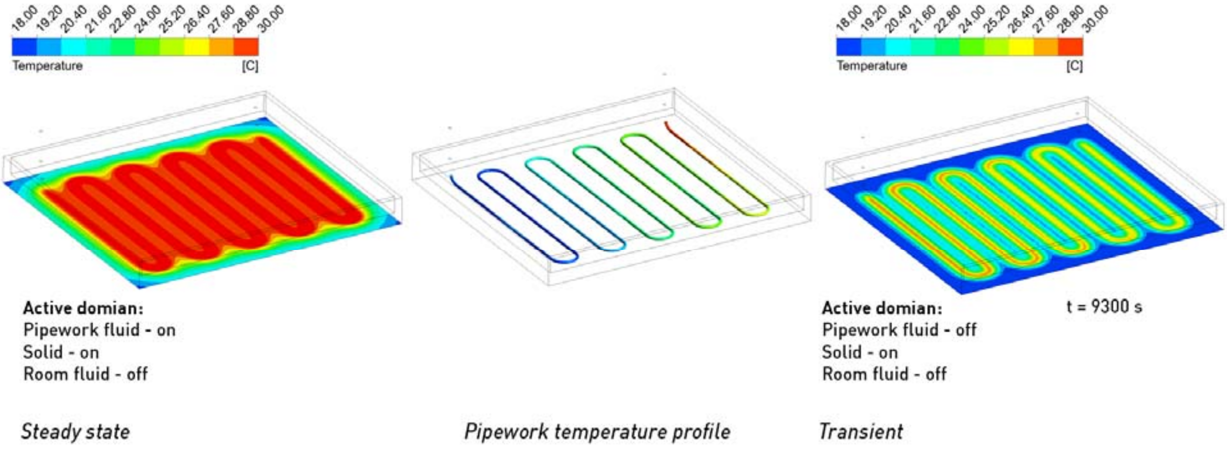
The comfort model was completed by combining the systems model with an additional room fluid domain (Figure 7a). The wall and floor boundary conditions were set using the shell conduction method (Fluent, 2016). Virtual computational cells are created and these cells represent material layers of the wall (Table 1). This is equivalent to a wall U-value. The surfaces can be internal or exposed to external conditions depending on the free stream temperature and the heat transfer coefficient. The inlet boundary condition is uniform velocity and it is set based on a room air change rate of 1.2 h^{-1}. The inlet air temperature is 12°C. Wall-x is the only boundary exposed to external weather conditions. The boundary condition settings of the surfaces using the shell conduction method is shown in Table 1.

As with the transient system model, the pipework fluid domain is suppressed for the comfort model. A wall temperature profile is applied to represent the hydronic heating pipework.

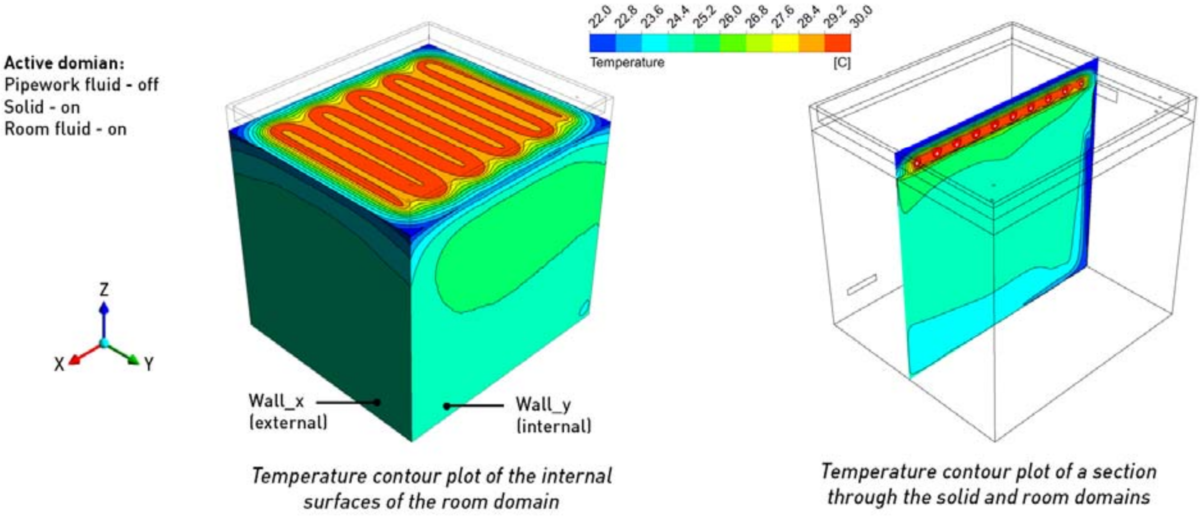
The k-omega STT model turbulence model was used for the comfort model. This selection is based on the study completed by Gilani et al., which showed that the k-omega STT model and the standard k-omega model



(a) Geometry



(b) Systems model



(c) Comfort model - Steady state

Figure 7: Simulation process (a) Geometry of the solid and fluid domains (b) Systems model results (c) Comfort model results.

models outperformed other turbulence models in cases for predicting stratified air in an internal zone with a low Reynold's number. To account for natural convection in the fluid domain, the density property of air was set as an incompressible ideal gas.

Fluent provides a number of radiation models, which can be applied to problems dealing with radiant heat transfer in buildings. The Discrete Ordinates (DO) radiation model can be coupled with a Solar Load Model. This provides a method for calculating the solar radiation entering the computational domain. In addition, the Surface to Surface model is useful for simple geometries. All of these methods will be assessed over the course of the project. For this study, the Surface to Surface radiation model is used to estimate radiative transfer of the internal thermal mass.

Monitors of air velocity at two points in the fluid domain were used to track the convergence. The simulation was continued until the residuals were less than 10^{-3} and the point monitors showed no significant change over 50 iterations.

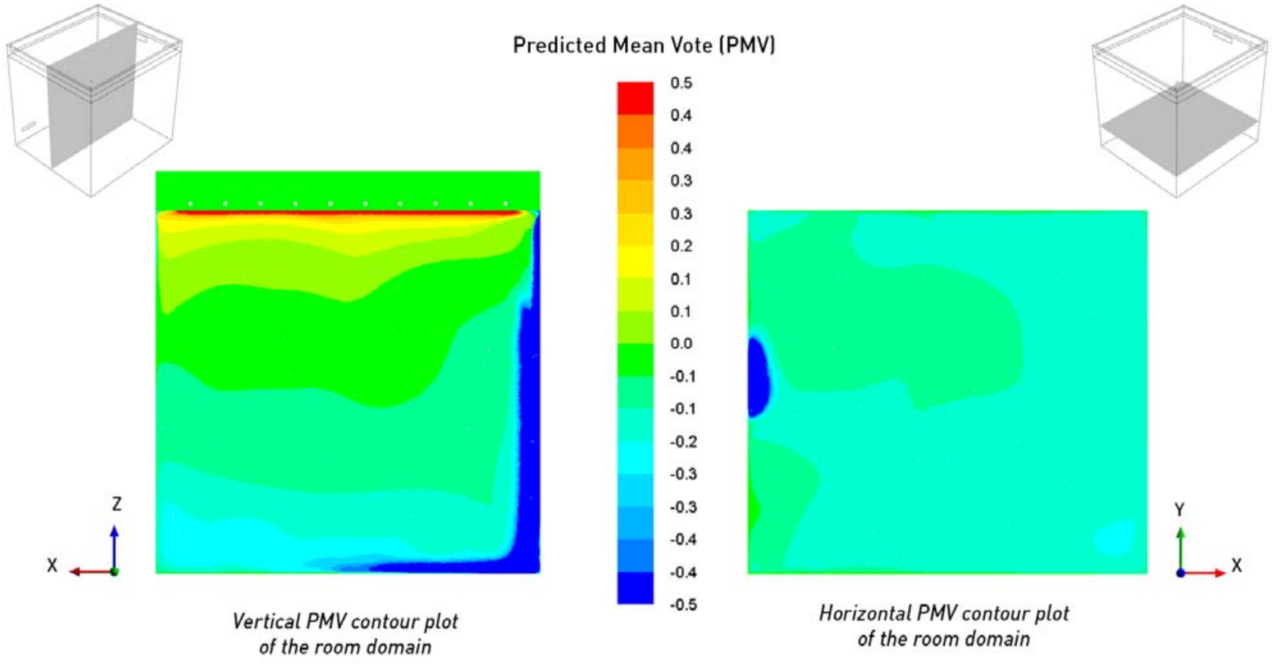
Comfort model results

As shown in Figure 7c, the result provides an estimate of the dynamic behaviour of the TABS panel and the influence of the internal thermal mass. In addition, the interaction between the TABS panel and the ventilation system is included. This can be displayed as surface temperature contours. The results output can be used to assess the active TABS panel, passive thermal mass and the ventilation system at critical design period.

Thermal comfort performance of the zone can be estimated using custom functions within the Fluent software. The PMV and PPD is calculated based on the solution data from the velocity and temperature fields. These calculations are dependant on inputs for relative humidity of the internal zone, the clothing value of the occupant and the metabolic rate of the occupant. Figure 8, shows results for the internal zone with a relative humidity of 50%, a clothing ensemble value of 0.49 and a "seated relaxed" activity. Figure 8 highlights the ventilation system as a source of thermal discomfort when the air supply temperature is 12 °C, during the winter period.

Table 1: Boundary condition settings.

Surface	Inner layer material	Inner layer thickness (m)	Outer layer material	Outer layer thickness (m)	Free stream temperature (°C)	External heat transfer coefficient (W/m^2 K)
Wall_x	Concrete	0.15	EPS Insulation	0.20	0	25
Wall_-x	Gypsum	0.05	EPS Insulation	0.20	20	7
Wall_y	Gypsum	0.05	EPS Insulation	0.20	20	7
Wall_-y	Gypsum	0.05	EPS Insulation	0.20	20	7
Floor	Concrete	0.2	EPS Insulation	0.15	20	6



Vertical PMV contour plot of the room domain

Horizontal PMV contour plot of the room domain

Figure 8: Comfort model – Predicted Mean Vote (PMV) results.

Discussion

The computational analysis framework presented will be used to design the first functioning prototype, which will be installed in an experimental building (HiLo) in Zurich, Switzerland. This installation will be used to calibrate the numerical models through experimental measurements. Before the first prototype is constructed, further investigation of the numerical modelling is planned.

As the geometry involves thin elements with relatively large surface areas, a key task is to manage the computational resources in terms of mesh size. The suppressing of fluid zones by the use of wall profiles is a good method of reducing the computational mesh size, as the fluid mesh is more demanding in terms of element density than the solid domain.

The simplified geometry TABS model will be used to investigate the limitations of using virtual computational cells with the shell conduction method to model the internal thermal mass. In addition, the benefits of using a polyhedral mesh will be investigated.

For the system model, the mesh density of the fluid domain is directly related to the selection of the turbulence model and wall functions. While the k-omega STT model has been shown to be accurate, this model requires a y* of between 1 and 3, which results in a high density mesh. A numerical sensitivity analysis study will be completed to assess the possibility of using a less demanding combination of turbulence model and wall function. For the comfort model, the work completed by Gilani et al., has indicated that the k- epsilon models are not suitable for the room fluid domain.

As the building geometry and energy systems become complex, the tasks of the energy domain tend to be merged. For example, the building services design for panel thermal performance and the building physics calculations for envelope thermal losses. Both of these tasks can be completed using high-resolution analysis. Therefore, it may be more efficient to combine or strongly align these tasks within the energy domain.

While the research and development phases are dependent on high-resolution analysis, it is not clear if this level of detail will be required in a design office setting with the constraints of building regulation derived from Swiss and European Union building energy targets.

Conclusion

This work investigates the use of high-resolution analysis for complex building systems. Methods to manage computational resources are outlined. By taking advantage of the steady state behaviour of the hydronic heating and cooling system, the simulation can be divided into a number of stages. While the results presented are related to a model with simplified geometry, a modelling framework is demonstrated to provide design feedback in terms of energy performance and thermal comfort.

The framework described in this paper has been developed for a lightweight concrete floor with TABS to improve the system control and the related system efficiency. Further, the proposed method offers a framework to strengthen the link between the HVAC and the control system design of TABS by providing high resolution thermal and comfort analysis.

Acknowledgement

The authors would like to acknowledge the contribution of Tomas Mendez Echenagucia (BLOCK Research Group), Dave Pigram (Supermanoeuvre), Filomena Di Dio, the NEST team at Empa and the various consultants involved in the project. This research was supported by Climate-KIC through the building technology accelerator (BTA) program.

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