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Thermal Comfort-CFD maps for Architectural Interior Design

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Abstract

Within the context of nearly Zero-Energy Buildings, it is debated that the energy-centred notion of design, proposed by regulatory frames, needs to be combined with a further focus toward users' comfort and delight. Accordingly, the underlying theory of the research is that designers should take responsibility for understanding the heat flows through the building parts and its spaces. A design, which is sensible to the micro-thermal conditions coexisting in space, allows the inhabitants to control the building to their needs and desires: for instance, maximising the benefits of heat gain from the sun moving a series of internal partitions so as to avoid the danger of over-heating.
It is thus necessary that existing simulation software tools are tested to the purpose of modelling and visualising the indoor thermal environment complexity. The research discusses how thermal comfort maps, which are prepared with the use of Computational Fluid Dynamic simulation method, could integrate energy simulation outputs to uphold qualitative architectural design decisions. Mean radiant temperature maps were thus used to design the retrofit of a small educational building in Copenhagen. The thermal opportunities of movable interior partitions (operated by the users) could be estimated, providing a new layer of information to the designer. The applicability of the thermal maps within an architectural design process is discussed adopting standard energy simulation comfort outputs as a reference. The capabilities and the limitations of the method are appraised.

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Keywords: Building Retrofit; Thermal Comfort Map; Computational Fluid Dynamic; Mean Radiant Temperature; Architectural Design Process

1. Introduction

On a global average, building-related activities consume more than 40% of a country's energy. The design based reduction of buildings energy consumption is an issue that the architectural practices are facing. In this context, the EU sets ambitious targets to ensure that from 2020 all new buildings will consume very little energy and has created the term "nearly Zero-Energy Building" or nZEB. Such policies are encouraging the use of energy simulation, which provides a prediction of the building consumptions and indoor conditions. Energy simulation is based on the concept of thermal zones, each of which is defined by single calculation points, which is an accepted computational

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approximation of the heat complexity of a building. For example, energy simulation tools such as EnergyPlus do not model thermal stratification of air temperature within a space, nor model accurately a grid of points that constitute a space.

In reality, a single energy thermal zone present several thermal micro-conditions. This is particularly the case of existing buildings [1] where there are multiple microclimates and thermal nuances within the same environment, which are leading to the concurrence of several mean radiant temperatures (MRT) inside a space. Existing buildings and historical buildings have thermodynamic logics, which are more complex than in contemporary, high isolated, and HVAC dominated ones. It is here argued that the thermal environment should be modelled to drive retrofit interventions. More specifically, thinking of architectural design process, it is considered key the use of visual maps of thermal comfort conditions generated by design. It is thus considered potential to use thermal maps of design scenarios as information that is complementary to energy simulation outputs. Temperature maps (i.e. mean radiant temperature map) can be calculated with Computational Fluid Dynamic (CFD).

The intention of integrating an energy modelling information with localised information of the array of comfort conditions as a simple logical argumentation. Occupants do not feel the heat loss from the building. They fell heat loss from their skin, ergo it fundamental to model the intimate infrared relationship that occupants' bodies have with all of the surrounding surfaces of the room. This type of information could be calculated for specific points even with energy simulation methods. However having a large the number of points requires a very laborious and customised inputting process. Nevertheless, the visualisation of the results is not automatic, and specific post-processing (e.g. with parametric graphical tools such as Grasshopper) will be required.

Moreover, what is the most important factor is to have spatial information (maps) that considers the impact of early design decision that is targeted to buildings that may have in different future functions. It is thus selected to adopt a metric such as the Mean Radiant Temperature (MRT). Following Standard ISO 7726 "The mean radiant temperature is the uniform temperature of an imaginary enclosure in which radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure." and ASHRAE 55 define MRT as "the uniform surface temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform space (…) It is a single value for the entire body and may be considered a spatial average of the temperature of surfaces surrounding the occupant weighted by their view factors on the occupant.".

Obviously, MRT is a dominant element in the thermal comfort equation, which is a fundamental part of indoor environmental quality and building performance. This study looks at modelling the human comfort within an indoor environment, weighing MRT within an architectural design process. The MRT describes one of the main traits of the thermal environment. It is an intention to exclude from this map other environmental factors such as ventilation and air temperatures (in addition to humidity) which are strongly related to HVAC operations and users preferences. Within this discourse, a specific and crystallized operation of the building (e.g. a fix air temperature) is considered inadequate. It is thus necessary to create a map of thermal conditions that is free from the bias given by a specific air temperature. By not using comfort indexes are excluded personal factors related to the characteristics of the occupants (metabolic rate and clothing level) the latter are air temperature, mean radiant temperature, air speed and humidity). Here there is another factor that brought the authors to exclude PMV maps: the indoor thermal comfort equations that are at the base of standards such as PMV are based upon extensive indoor survey results, and the survey was unlikely carried out in extreme conditions, such as under direct solar radiation of a window.

2. Bridging the gap between CFD research and the Architectural Practice

The context of its simulation is briefly presented. During the past two decades, Computational Fluid Dynamic (CFD) has been studied intensively in the domain of building environments. The literature on CFD and buildings application accounts for nearly 100,000 of papers, the particular use of CFD to simulate indoor microclimate counts about 1,500 articles. The latter is mainly concerned with topics such as indoor air quality [2] naturally ventilation [3, 4], mechanical ventilation [5] or HVAC [6]. A few studies describe the use of CFD to evaluate thermal comfort [7-11]. They are however related to a single space or room, in most of the cases, CFD is used to verify design solution and to compare models insulation with probe monitoring data. However, little research was carried out about to CFD in the context of designing a building with the use of MRT as a design factor. The relation between MRT and space geometry was examined Kalmar [16], Frontini et al. [17] and Chung et al. [18], however, there is no research concerning its use to support architectural design decision with comfort maps.

On the other side, the design practice is still far from implementing CFD based thermal comfort metrics in design. Architectural practices consider CFD as a poorly effective technique, which is often only performed a few times during a building design/construction cycle and primarily for verification purposes [12-15]. The second issue is related to the complexity of computation. The interaction of natural ventilation flow with thermal heat transfer properties of solid materials is computationally very intensive and thus not well integrated into engineering and design prediction tools yet. It is here investigated the integration of CFD for the calculation of MRT in an architectural design process. The study examines the incorporation of MRT into the early stages of design when critical decisions, including those pertaining comfort conditions, should be held. The scope of the paper is to contribute to bridging the knowledge generated in research with the nature of architectural design. The connection is not easy, yet, the inclusion of researchers in practice with knowledge in simulation, new user-friendly CFD tools and increased computational power are factors that should facilitate the process.

3. Mean Radiant Temperature: Calculated via Energy Simulation or CFD?

Thermal Comfort [21], Adaptive Thermal Comfort [22-24] and Comfort and Heritage [25, 26] are the broad contours of the study. The design method is based on the consideration of the full spectrum of thermal conditions within spaces, which are predicted, with the use of Mean Radiant Temperature calculated with CFD. MRT is regarded as the primary driver for architectural and constructive developments [19, 20] since it describes the radiant exchange between the human body and surfaces, thus being an indicator of the properties of the space geometry and the construction features. Calculation with building energy simulation Tools (e.g. EnergyPlus), could provide a calculation of MRT according to ISO standards 7730 [27] and/or ASHRAE 55 [28]. According to Energy Plus engineering reference "There are three options to calculate the mean radiant temperature in the thermal comfort models. One is the zone averaged MRT, another is the surface weighted MRT, and the other is angle factor MRT":

The area averaged MRT is calculated on the assumption that a person is in the centre of space, whereas people may be located in different part of space. The surface weighted MRT is calculated in consideration of the surface that a person is closest to.

The surface weighted MRT is the average temperature of the selected surface and zone averaged MRT and is intended to represent conditions in the limit as a person gets closer to a particular surface. In that limit, half of the individual's radiant field will be dominated by that surface and the other half will be exposed to the rest of the zone. Thus the surface weighted MRT is only an approximation.

The angle factor MRT is the mean temperature of the surrounding surface temperatures weighted according to the magnitude of the respective angle factors and allows to more accurately predict thermal comfort at a particular location within a space. However, this type of input needs to be calculated for single or multiple points and by setting a grid: visualising results for space requires a significant workaround and a specialist in the software need to involve.

Regarding the accuracy of the calculation, it should be noticed that the effective temperature of the screen/glazing combination that in energyPlus is used to calculate windows contribution to the zones mean radiant temperature (MRT), is calculated with respect only to long wave radiation. Therefore, the mean radiant temperature calculation for energy does not take into account direct sunlight through a window. "A person standing near a window" is the case when indoor thermal comfort calculation are quite inaccurate if performed with energy simulation. Thermal CFD is here considered due to its ability to visualise results creating a map of MRT conditions. Within the aim of using indoor microclimatic predicted data, obtainable from the CFD thermal simulation there are a few factors to be considered. MRT can be simulated by a series of architecturally friendly thermal CFD tools such as DesignBuilder® CFD [29] or Autodesk® CFD [30]. The latter it is used for the following experiment with standard setting utilised (k-turbulence model). Both short and long wave radiation are modelled with Autodesk CFD.

4. Case Study and Methodology

A user-centered case of retrofit is simulated to test the applicability of CFD. A building within the campus of the Royal Danish Academy in Copenhagen, which is flexible in its functions (it can be dedicated to students' daylighting studies, as well as for lectures and at times it can be used to host researchers working spaces), is used as the case study. Given such variety of scenarios, a system of movable partitions is considered and the space can be configured following a variety of logics, which are not the object of discussion here. The idea is that various configurations of the interior can lead to a variety of thermal conditions. To isolate the performance relation between MRT and interior partitions layout, a series of CFD simulations were run. CFD –MRT analysis map were generated for typical summer and winter days, both at noon. The simulated building, originally built as a factory and a warehouse (Building 155 – Fig. 1), is today used as a daylighting studying facility for architectural students. A 3D model of the building was generated in Rhino and imported into the Autodesk Thermal CFD tool.

Assemblies' temperatures are not derived from energy simulation; this is because predictions are roughly averaged by the full extent of a surface. Boundary conditions such as the temperatures at internal surfaces were defined in the CFD tool, which accounts for both the effect of short and long wave radiation. Other boundary conditions such as film coefficients were derived from literature. Some of the environmental conditions (i.e. outdoors temperatures, air velocity and direction) were extracted from an EPW weather file which was compiled on the basis of data gathered by an onsite weather station. Before running a CFD analysis, the geometry was automatically meshed by the CFD tools into small pieces called elements. Meshing is an important feature that is facilitating the adoption of CFD in architectural design. It simplifies set-up of analysis models resulting in less time spent assigning mesh sizes.The quality and number of elements have a direct impact on the computation time and soundness of the analysis results'. CFD experiments were carried out to simulate variables of indoor air before/after installation or removal of partitions. Every steady state analysis had required multiple iterations before convergence (500 to 700 iterations depending on the scenario).

Fig. 1. Building 155- KADK Copenaghen

5. Mean Radiant Temperature Maps to Configure Thermal Conditions

A few retrofit strategies are simulated and later discussed according to a typical summer day (table 1) and a winter scenario (table 2). The design is mainly concerned with movable interior partitions. The internal partitioning is here an act of demarcating spaces into multiple volumes for various uses and to create the specific thermal conditions. The interacting effects of partitions towards occupant's thermal comfort and building energy consumption is found to be often poorly considered in nZEB, the scope of the MRT map is thus the one of providing to the design team the understanding of preliminary scenarios performances. Interior partitioning poses a significant threat to occupant's comfort, as it shown in this study. Therefore, it is key studying the interacting effects of partitions on thermal comfort quality. The building is simulated, and MRT maps are reported in the occupied zones at the height of 1.1 m above the floor. Taking the worst-case scenario, the upper floor of the building (in winter is endangered by significant heat losses via radiation exchange with the sky, and in summer is exposed to a substantial amount of sun radiation) the full potential of partitions of manipulating comfort was assessed. The Building envelope is modified so that it compliant with the U values prescribed by Copenhagen building code. A layer of 10 cm of insulation is attached to the interior wall. In winter, a low-temperature radiant floor is utilised in the model, in summer no HVAC system are considered. Here is a list of the design options and the MRT maps:

Open Space - Baseline Case. An entirely open space. It should be noticed how the MRT gradient crosses the space from side to side with differences up to 8 degrees in summer and 3 degrees in winter.

Volumes Subtraction (option 1 and 2) It was analysed the thermal significance of small volumes subtractions, being these a possibility for advancing daylighting conditions and create green roofs at different building heights. The subtractions generate Summer overheating: glazed partitions creates greenhouse effects that lead to high MRT values. Adding internal partitions yields to further reduce the overheated areas (option 2). In winter, having larger thermal zones could result in a substantial expansion of sectors with a higher MRT. This simple observation further suggests the use of movable partitions, so that seasonable configuration can be adopted.

S-shaped internal partitions are speculatively placed within the space to distinguish interior microclimates. It is plausible to create spaces and adjacent rooms where the MRT varies by 5°C just by the arrangement of partitions. It should be remarked how the solution could be seasonally adapted to create areas with moderate summer MRT, and in winter to create larger areas with higher MRT.

Rotating Partitions System (configuration 1 and 2). The study pointed to the design of movable partitions that users can control to adjust microclimates. In Summer MRT can be decreased for a large surface, and the opposite can occur in winter (configuration 2).

Table 1. Building 155 CFD simulation. Design variations are compared at noon of a typical summer day.

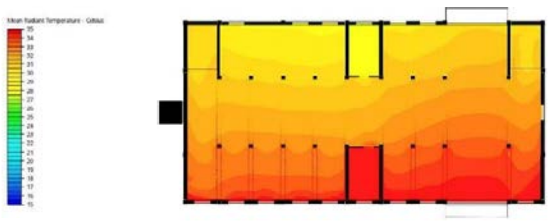
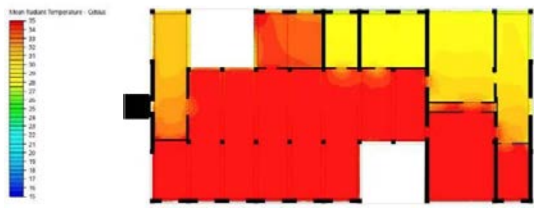
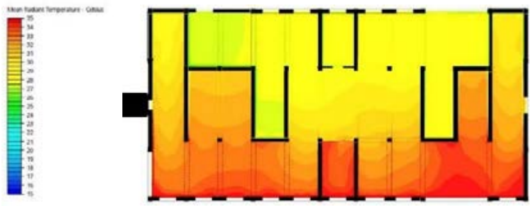
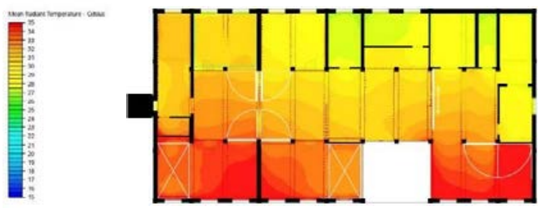
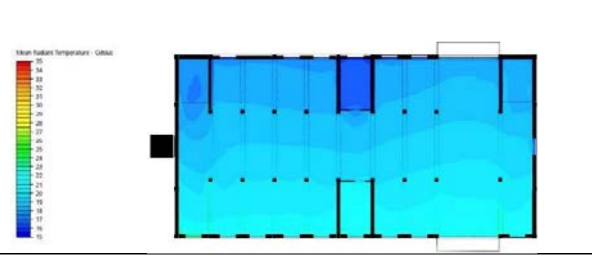
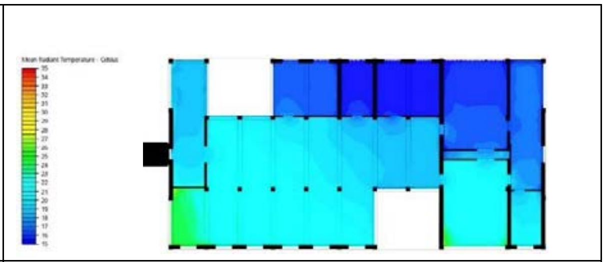
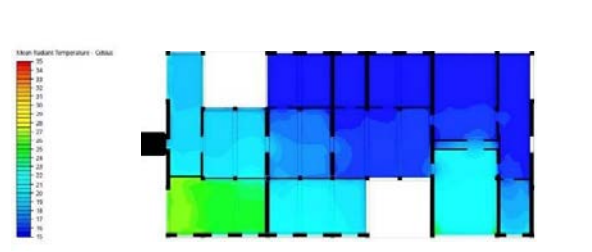
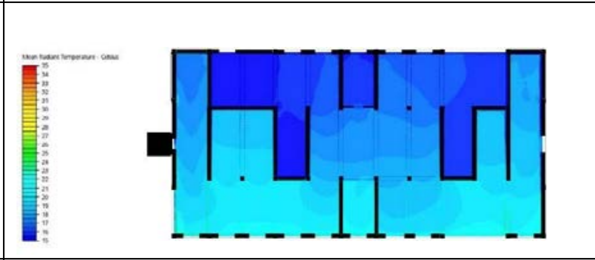
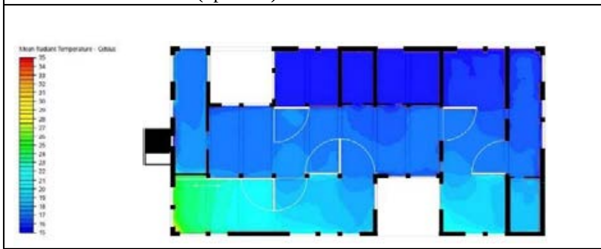
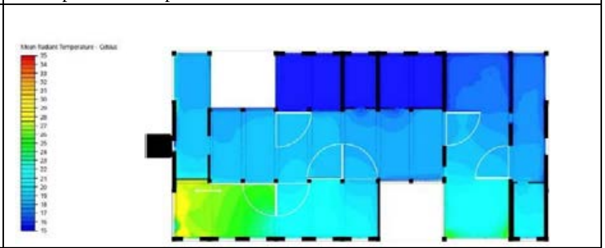
	
Open Space - Baseline Case	Volumes Subtraction (option 1)
	
Volumes Subtraction (option 2)	S-shaped internal partitions
	
Movable Partitions System (configuration 1)	Movable Partitions System (configuration 2)

Table 2. Building 155 CFD simulation. Design variations are compared at noon of a typical winter day.

	
Open Space - Baseline Case	Volumes Subtraction (option 1)
	
Volumes Subtraction (option 2)	S-shaped internal partitions
	
Movable Partitions System (configuration)	Movable Partitions System (configuration 2)

6. Discussion and Future Work

The research concerns the adoption of computed Mean Radiant Temperatures Map as a way to account for comfort implications with a simple graphic, yet rich of information at a high density of distribution. This is meant to support architectural design decision. The CFD was utilised to determine MRT according to various scenarios that can be designed throughout a Conceptual Phase of Design. Colours based comparisons are shown in greater resolution and details offering qualitative information that an energy simulation would not offer. The simulation provided a full landscape of MRT-thermal conditions, which can be easily related to spatial configurations, thus highlighting how internal partitions are an opportunity to design thermal conditions. Such type of understanding would it be difficult to be obtained with energy simulation tools which provide sporadic punctual information and with no tool today able to create a map of MRT conditions.

Some lengthy discussion is here announced and should be the object of more detailed investigations. The CFD experiments show that Mean Radiant Temperature is increased in some specific regions according to the dislocation of partitions. Thermal comfort can consequently be improved by adjusting partitions location. This information is leading to look at retrofit beyond the typical approaches suggested by code and energy simulation (typically, the focus is on elements such as the lack of insulation of the building envelope and poor performance of the components of heating and cooling systems). Significant attention should thus be given to architectural design solutions that are targeted to comprehend the occupants' physiological needs of living in a thermal stimulating environment [31-33].

The full process seems to be compatible with a firm architectural with a sustainable design specialist "on board", who has a basic understanding of CFD simulation. This condition is rare at present. Relating to the Status Quo of today practice, it seems that the proposed method is more applicable by consultants to support an architectural office. Further factors to be accounted are the time of pre-processing and computation, which does not seem to be longer, based on the author's experience, to the one required by energy modelling. A further comparative study of the computation performance of CFD tools when modelling indoor conditions should be developed in a second stage. In this experiment, preparation of the model and 12 CFD scenarios computation, performed with a standard dual-core PC, required a total of 30 hours of computation. Even considering that the majority of the architectural practices does not have access to a cluster or cloud computing [34] the proposed method may have a potential of implementation.

7. Conclusion

As the focus moves from Energy-Centric notions of Building to a User-Centric understanding of spaces, it is key to have the tools that allow modeling the thermal conditions. Comfort is often achieved by installing lots of expensive equipment and spending lots on running it so the building can provide an acceptable temperature. A sensible building design allows the inhabitants to control the building to their needs and desires: for instance moving partitions seasonally, as shown in the case study. The paper discusses how information that is provided for a limited number of points in space, such as the one provided by energy simulation are a rough approximation of reality. More importantly, accounting for several points in a space and creating an MRT map with energy simulation, would require a significant work of post processing. Simply put, energy simulation tools are not conceived to provide a high-density information of thermal indoor qualities. The paper thus explores the application of MRT maps, calculated with CFD, for building indoor thermal design. A full mean radiant temperature map at high resolution it is shown to provide visual information to aid in the design of user-comfortable and environmentally friendly buildings.

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