Towards an alternative cooling: Optimisation of the successive use of the cooling systems from passive to active - Development of design and control strategies of the hybrid cooling

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ABSTRACT

Due to global warming, severe problems of buildings overheating during summer in temperate and hot climates arise. Thus, there is an increasing use of air conditioning. However, alternative passive and soft cooling systems exist to address comfort and energy savings issues, such as natural ventilation or ceiling fans, that consume less energy. Although they are well-known today, their use remains under-enhanced. CoolDown project, funded by the French National Research Agency (ANR), aims to define the tools and methodology to optimise the successive use of passive, soft and active systems to maximise comfort for occupants while minimising energy consumption in summer, hot seasons or heat waves. The methodology of this project is hereafter presented to achieve two mainly two types of outputs: (1) the definition of metrics to quantify the building potential and performance from thermal comfort and energy perspectives, and (2) the development of tools and algorithms to optimise the coupling of building passive and active cooling systems, both in the design and operation phases.

KEYWORDS

Summer comfort, Mixed mode buildings, Hybrid Cooling Solution, IEQ, Multi-criteria optimised control strategies, Performance Guarantee

1 INTRODUCTION

In the current context of global warming, severe problems of buildings overheating during summer in temperate and hot climates arise. As a result, these hot periods lead to an increase in the use of air conditioning and, thus, to an increase in energy consumption and peak electricity demand at the global scale. However, alternative and original so-called combined passive and soft cooling solutions exist to address both comforts in hot climates and energy savings issues,

such as natural ventilation and ceiling fans that consume much less energy. Furthermore, the COVID-19 crisis highlights the importance of building ventilation with clean air in the foreground of natural ventilation. Some cooling solutions combining passive and low energy (soft) solutions with active, more energy-consuming systems can reduce energy consumption drastically. Nevertheless, although those mixed-mode solutions begin to be well-known today, their uses remain underwhelming in the building field, especially in temperate and tropical climates. To overcome this issue, 5 main scientific and technical barriers have been identified. The first Scientific and Technical Barrier (STB1) lies in a need for knowledge of the actual performance and the impact of the passive and soft cooling solutions and especially their combined uses with active systems (STB2). Moreover, in this notion of performance, both the energy and the comfort aspects are important issues. However, if the quantification of the energy consumed through an indicator is quite easy to reach, it is challenging to quantify and ensure thermal comfort in diverse hot climates considering a mixed-mode cooling solution combining passive, soft and active systems (STB3). Indeed, considerations of comfort are different in according to the cooling system and the occupant habits. It has been notably shown that the occupants' comfort expectancy is much higher when using Air Conditioning (AC) than for Naturally ventilated (NV) buildings. Mixed mode cooling solution being at the edge of those AC and NV ones, comfort should be quantified in accordance. Two other challenges appear then. First, if the energy performance guarantee is largely studied in the state of the art in heating conditions, energy performance guarantee in cooling conditions (STB4) remains less investigated, especially in the presence of natural ventilation and use of ceiling fans providing a consequent air velocity. Second, considering comfort in the verification protocols (STB5) is usually not considered in those works. Finally, the economic and environmental aspects also need to be considered to ensure the potential and consistency of optimised solutions.
The objective of this article is to present the methodology which will be developed during the *CoolDown* project. Its overarching objective is to define tools and methodology to optimise the successive and combined use of passive, soft and active solutions to maximize controlled comfort for occupants while minimising energy consumption in summer, hot seasons or heat waves to face the climate change impact in the Architecture and Engineering Industry (AEC) industry with a focus on existing office buildings.

2 STATE OF THE ART

As mentioned hereabove, the current context of global warming leads to a drastic increase in air-conditioning use and, consequently, energy consumption. Natural ventilation and ceiling fans showed their efficiency as alternative solutions, but their cooling potential tends to be reduced with higher outdoor air temperatures, especially during heat wave periods. Therefore, natural ventilation by itself, even coupled with ceiling fans, may not be sufficient to ensure the comfort of occupants throughout the year. In this context, there is an intermediate solution, defined as mixed cooling (MM: mixed mode cooling) according to the definition of (Brager, 2006). This solution, called *changeover*, is defined as cooling by air conditioning and natural ventilation operating in a differentiated manner on a seasonal or daily basis. In addition, the use of ceiling fans (0.5-2.0 m/s) makes it possible to lower the perceived temperature and consequently delay the turning of the air conditioners and raise the setpoint temperatures of the latter. It is then possible to have a cascade sequence of different solutions (Natural Ventilation, Natural Ventilation + Fan, Fan + Air Conditioning). Unlike naturally ventilated and air-conditioned buildings, the mixed-mode building does not have a dedicated comfort model. More generally, two families of comfort models are today represented in standards and literature. The first contains models based on steady-state heat balance equations, such as the one-node (Fanger, 1970) or the two-nodes (Gagge, 1986) thermal regulation models. They make it possible to calculate the PMV (Predicted Mean Vote) or SET (Standard Effective Temperature) indices and give a prediction of the comfort felt by the user after a physiological reaction caused by thermal stress (Gao et al., 2015). To do this, they require a multitude of input parameters (radiant and air temperature, airspeed, relative humidity, clothing, metabolism, etc.). The second contains models from satisfaction surveys in a heterogeneous selection in terms of building and location. These are the models of comfort zones on the psychometric diagram, initiated by (Givoni, 1992) and the American (based on the RP-884) and European (based on the SCAT) adaptive models. They put in linear relation the indoor climatic conditions of comfort with outdoor running mean temperature. There are also regional variations in the Chinese (GB/T 2000), Dutch (ISSO74) and Indian (IMAC) standards. These adaptive models emerge from the observation that the thermal sensation votes from the PMV, initially validated in laboratory conditions, were different from the real votes in naturally ventilated buildings where the occupants benefit from a great opportunity for adaptation to restore their comfort. A dichotomy is thus established between comfort model type and building cooling modes in the standards governing comfort in the AEC industry. It should be noted that in the standards, as in the literature, the recommendations are in line with the use of Fanger's PMV-PPD (Predicted Mean Vote, Predicted Percentage Dissatisfied) model in air-conditioned buildings and the Adaptive Model (AM) in naturally ventilated buildings. However, the most common standards, ANSI/ASHRAE Standard 55 (USA), ISO 7730-2009 and EN 16798 (Europe, ex EN 15251) do not mention any real guide for the evaluation of comfort for this type of mixed-mode cooling (Kim et al., 2019; Carlucci et al., 2018). This is particularly true in hot and humid climates which lack research in the field as mentioned (Rodriguez and D'Alessandro, 2019). EN 16798 or IMAC (India) do offer an openness towards the use of the adaptive model for mixed-mode buildings but specifies that it is only valid if no air conditioning system is in operation, which rules out the simultaneous use of fans and air conditioners. Our project will then address this question of the suitable metrics for quantifying the comfort in the presence of a mixed-mode cooling strategy in a large diversity of climates.

At a different comfort complexity level, a new neurophysiological human thermal model based on thermoreceptor responses, the NHTM model, has been developed by (El Kadri et al., 2020) to predict regulatory responses and physiological variables in asymmetric transient environments. The passive system is based on Wissler's model (Wissler, 2018), which is more complex and refined, it simulates heat exchange within the body and between the body and the surroundings. The active system is composed of thermoregulatory mechanisms, i.e., skin blood flow, shivering thermogenesis, and sweating. The skin blood flow model and the shivering model are based on thermoreceptor responses. The sweating model is that of (Fiala et al., 1998) and is based on error signals. This latter has also been used to improve the Gagge model (Vellei et al.,2020). In this project, this model will be implemented, and the results will be compared to the other classic thermal comfort models previously mentioned.

Afterwards, those suitable comfort metrics would be used to feed the mixed-mode cooling control strategies. In the literature, some authors have already proposed intelligent solutions to control cooling systems by combining alternatively an active energy-consuming air-conditioning and a passive natural ventilation device (Emmerich et al., 2006), (Zhai et al., 2011), (Hu et al., 2014), (Chen, 2019). However, the aspect of occupant comfort and the simultaneous use of the different cooling systems should have been considered in those works. Our project is to go further by associating simultaneously the passive, soft and active cooling systems with a double objective of both energy and comfort. To reach the flexibility of the control algorithm, the chosen method will be fuzzy logic. One advantage of this technique resides in the fact that it allows modelling the user behaviour of a system instead of the system itself. Given that, it requires global concepts to describe approximate variables instead of precise numerical values. It provides then a large flexibility of the control algorithm. Some authors have already shown the efficiency of the fuzzy logic for ventilation control (Dounis et al., 1996), (Eftekhari et al., 2003), (Homod et al., 2014). Our methodology will be built on those works.

Once the mixed-mode control strategies are defined, they will be tested, and the following required stage will consist in the ability to guarantee their performance according to energy and comfort issues. Guarantee the energy performance in buildings is a research topic more and more investigated in the recent years. As shown in the two successive IEA EBA Annex #58 dealing the intrinsic thermal performance of an envelope and #71 focusing on the performance in-use. To estimate the intrinsic performance which is a key point to ensure the quality of the on-site work compared to the design phase, methodologies (co-heating (Bauwens et al., 2014), ISABELE (Thebault et al., 2018), SEREINE, QUB (Ahmad et al., 2020)) are developed to quantify the heat loss of an envelope through conduction and the infiltration flowrate (Jay et al., 2020). This is particularly interesting to estimate the active systems' energy needs, whether hot or cold (Jay et al., 2021). All these methods focus on the energy use performance only. They do not consider the impact of comfort and quantify the relevance of natural ventilation or ceiling fans in the final energy consumption and their impact of the comfort.

3 METHODOLOGY

To define tools and methodology to optimize the combined use of passive, soft and active solutions, *CoolDown* workplan is articulated around 4 pillars (Figure 1). First one will focus on occupant acceptability and comfort followed by some occupant surveys. Second pillar will focus on active cooling systems with the development of a methodology to fine tune their sizing. Third pillar aims at optimizing the combined use of passive, soft and active cooling systems in term of sizing and control strategies. Fourth pillar targets to develop methodology for guaranteeing the actual performance of the hybrid cooling strategies considering occupants' acceptability and energy use. Last but not least, the work developed in this project will be supported by five (5) office buildings in real different climate areas (2 in Auvergne-Rhônes-Alpes, 1 in Centre, 2 in La Réunion). These buildings will be used throughout the project, first as a use case for the technical *CoolDown* development and then for alternative solution implementation to get real feedback on their efficiency.

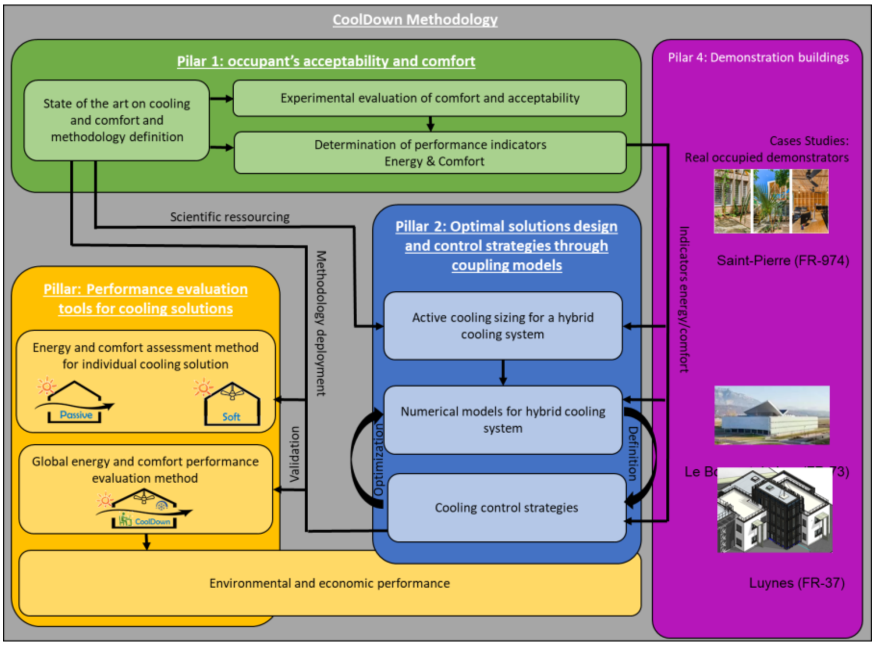


Figure 1: CoolDown methodology

3.1 Occupant acceptability and comfort

The acceptability of the occupants regarding the passive, soft and active cooling solutions is likely to be carried out by using a survey on a sample of a thousand people representative of the mainland and French outermost tropical population, by means of a telephone survey. This sampling will include a sample of occupants of non-equipped and equipped buildings. It will also integrate oversampling in regions experiencing recurrent episodes of high heat to anticipate future behavior induced by the effects of climate change.
Several experimental campaigns will be carried out in demonstrator buildings to obtain a first set of data corresponding to the initial state of the occupant's comfort. Twenty occupants' thermal comfort will be assessed using objective physiological measurements (skin temperature and heart rate) and declarative sensory questionnaires about their perceived thermal comfort. For each campaign, physiological and sensory responses will be recorded for one week for each participant, in a real occupied demonstrator in La Réunion. Their environment will also be monitored (temperature, humidity, radiation). This data set will contribute to building and optimising a thermal comfort prediction model, which will be validated with the data from a second set of experimental campaigns testing the optimized hybrid cooling solutions as described in *Figure 2.*

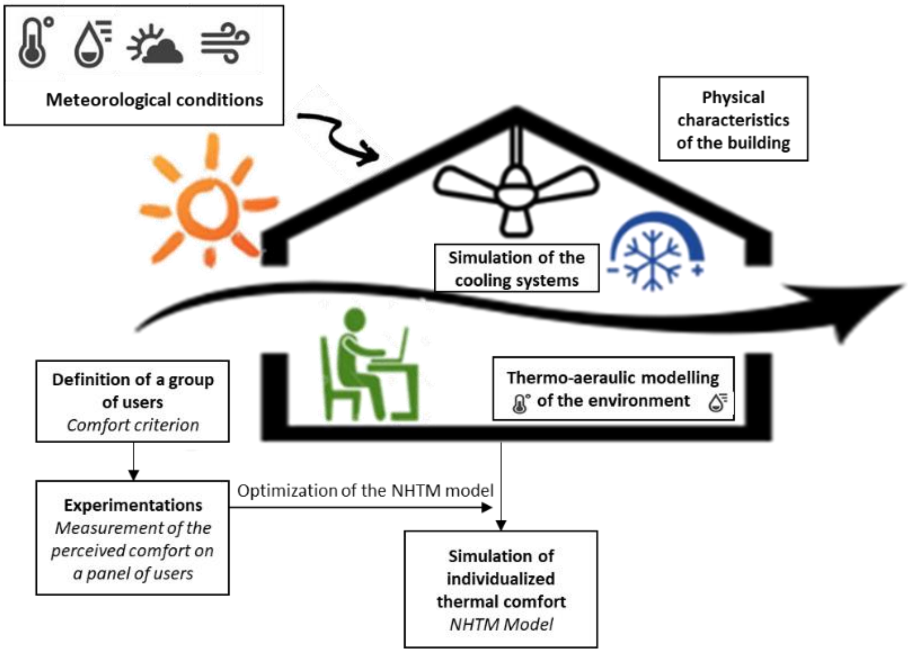
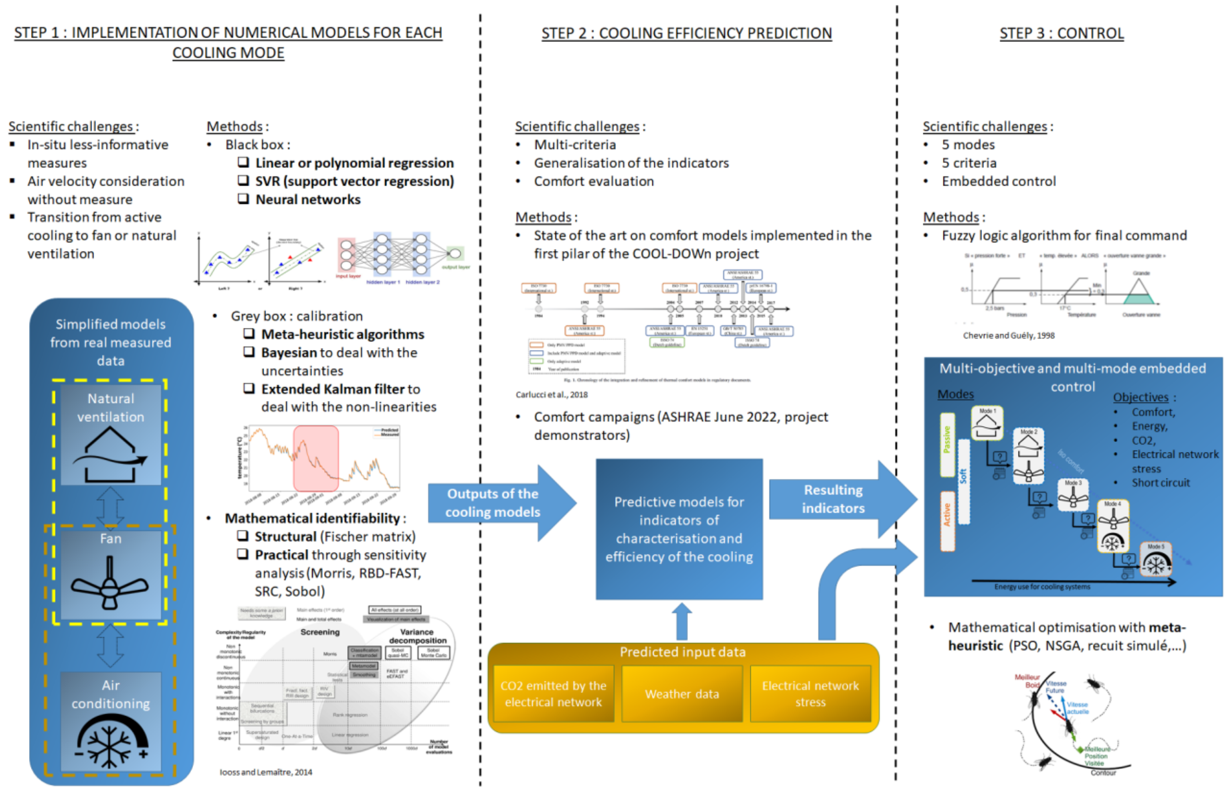


Figure 2: occupant acceptability surveys and model development process

3.2 Optimal solutions design and control strategies through coupling models

The project will target the optimization of the combined use of passive, soft and active cooling systems in term of sizing and control strategies. Better knowledge of active cooling system behaviour, flexibility, and complementarity regarding additional passive and soft modes are also studied. To do so, this task will combine numerical and laboratory experimentations with implementing and validating a hybrid cooling numerical model. To develop it as accurate as possible, numerical barriers appear through the choice and the coupling of the passive, soft and active cooling system sub-models. Furthermore, considering the metrics defined in the first axis, the mathematical optimization of the hybrid system sizing and control strategies will also be a major challenge.

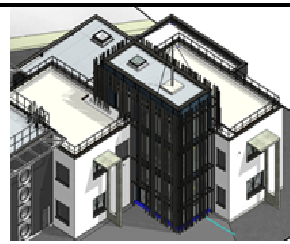


3.3 Performance evaluation tools for cooling solutions

Fourth pillar of *CoolDown* lies on performance assessment of the cooling solutions to ensure that the *CoolDown* solutions are efficient and to characterise their cooling potential and real performance. First, a work focuses on choosing and defining indicators to this end, then develops or adapting methodologies to measure and quantify these indicators. A two steps approach is foreseen. First indicators and methodologies are studied for standalone solutions including natural night ventilation, solar aperture, thermal inertia, and fans. Then, work is carried out on global methodologies and common indicators for the *CoolDown* solutions mixing different cooling modes. The target is to keep light monitoring strategies to replicate these methodologies at a large scale.

3.4 Case study to be used

Development and tests done in the other pillar of the project will be supported by four real occupied offices situated in different climate areas: Savoie (73), Indre et Loiret (37) and La Réunion (974). These buildings will first feed the other tasks as test cases thanks to the available monitored data and buildings characteristics to build on numerical models of these use cases. Following the results from Finally, each development will be implemented in at least one of the demonstrators to qualify its feasibility or quantify its impact.

	#1 La Reunion – Agence COArchitectes	#2 Mayotte Collègue de Bouéni	#3 Hélios INES	#4 Bluetek
Picture Responsible partner // Crédit Photo	 LEU Réunion//©Yannick Ah-Hot	 LEU Réunion // LAB Réunion	 CEA // CEA	 Bluetek // Cub Architecture
Year built	Before 1980 – refurbishment 2017	2019	2014	2022
Position	Saint-Pierre 974	Bouéni, Grande Terre, Mayotte	Le Bourget du Lac (73)	Luynes (37)
Climate	Koppen Tropical dry savanna (As)	Koppen Tropical wet savanna (Aw)	Koppen (Cfb) RE2020: H1c	Koppen (Cfb) RE2020: H2b
Surface	150 m^2	5536 m^2	7000m^2	200m^2
Usage	Architecture offices	Middle school + Admin. Offices	Offices + Labs + Training rooms	Offices + conf. room + staircase
Cooling solutions	Openspace, Singe Office, Meeting Room: AC + Fan + NV + double sided window doors openings Double Office : Fan + NV + Jalousies + louvers	We will only consider administration offices which is deisgned along a ventilation open atrium and benefits from AC and Ceiling fans. All opening are jalousie type.	In offices : Natural convection controlled manualy with specific windows and jalousies in the offices Openings in the Atrium Automatic vertical shading	Natural ventilation manually activated but with notifications from a control system. Geothermal cooling. The building is designed from wind driven natural ventilation. The staircase is automated.
Monitoring	Temperature, Humidity, Energy Use, fan behaviour (from Mai 2022)	To be installed. Well known building as LEU Reunion is part of the design team	Part of the offices are monitored in term of temperature and occupants comfort thanks to a dedicated	Energy, temperature, Humidity, CO2, presence detector, Illuminance.

4 CONCLUSIONS

Centred on three different challenges of an innovative cooling solution among the comfort evaluation, the control and the performance guarantee, the *CoolDown* project will address efficiency and energy performance cooling strategies. Specifically, the objective of this project is to implement a cooling solution leading to energy savings by limiting the use of the air conditioning while providing optimal thermal comfort. To do so, three cooling modes will be employed with passive, soft and active systems. The passive mode will mainly be linked to natural ventilation through dedicated large openings. Concerning the soft solution, it will be reached by using fans (mainly ceiling fans in tropical climates). And finally, the active cooling will consist of an air conditioning system. Based on both comfort and energy considerations, a successive mode control strategy will be implemented to maximize the efficiency and performance of building cooling.

5 ACKNOWLEDGEMENTS

The project *CoolDown* is funded by ANR under the number ANR-22-CE22-0014-06

6 REFERENCES

Ahmad, N., Ghiaus, C., & Thiery, T. (2020). *Influence of Initial and Boundary Conditions on the Accuracy of the QUB Method to Determine the Overall Heat Loss Coefficient of a Building*. Energies, 13(1), 284.

Attia, S. (2015). *Impact of different thermal comfort models on zero energy residential buildings in a hot climate*. Energy and Buildings, 102, 1-5.

Bauwens, G., & Roels, S. (2014). *Co-Heating Test: A State-of-the-Art*. Energy and Buildings, 82, 163-172.

Bouchié, R., Alzetto, F., Brun, A., Boisson, P., & Thebault, S. (2014). *Short methodologies for in-situ assessment of the intrinsic thermal performance of the building envelope.* Sustainable Places, Nice.

Brager, G. (2006). *Mixed-mode cooling*.

Carlucci, S., Bai, L., de Dear, R., & Yang, L. (2018). *Review of Adaptive Thermal Comfort Models in Built Environmental Regulatory Documents*. Building and Environment, 137, 73-89.

Chen, Y., & Z. T. (2019). *Achieving natural ventilation potential in practice: Control schemes and levels of automation*. Applied Energy, 235, 1141-1152.

Chen, W., Zhang, H., Arens, E., Luo, M., Wang, Z., Jin, L., et al. (2020). *Ceiling-fan-integrated air conditioning: Airflow and temperature characteristics of a sidewall-supply jet interacting with a ceiling fan*. Building and Environment, 171, 1-10.

Day, J. K., McIlvennie, C., Brackley, C., Tarantini, M., Piselli, C., Hahn, J., et al. (2020). *A review of select human-building interfaces and their relationship to human behavior, energy use and occupant comfort.* Building and Environment, 178, 1-14.

Dounis, A. I., & Balaras, M. (1996). *Indoor Air-Quality Control by a Fuzzy-Reasoning Machine in Naturally Ventilated Buildings.* Applied Energy, 54, 11-28.

Eftekhari, M. M., & Dascalaki, E. G. (2003). *Application of fuzzy control in naturally ventilated buildings for summer conditions*. Energy and Buildings, 35, 645-655.

El Kadri, M., De Oliveira, F., Inard, C., et al. (2020). *New neurophysiological human thermal model based on thermoreceptor responses*. International Journal of Biometeorology, 64, 625-639.

Emmerich, S. J. (2006). *Simulated performance of natural and hybrid ventilation systems in an office building*. HVAC & R Research, 12, 975-1004.

Erba, S., Sangalli, A., & Pagliano, L. (2019). *Present and future potential of natural night ventilation in nZEBs*. IOP Conference Series: Earth and Environmental Science, 296, 1-6.

Fiala, D. (1998). *Dynamic simulation of human heat transfer and thermal comfort (PhD dissertation*). Institute of Energy and Sustainable Development, De Montfort University Leicester.

Fanger, P. O. (1970). *Thermal comfort: Analysis and applications in environmental engineering*. New York: McGraw-Hill.

Gagge, A. P., Fobelets, A. P., & Berglund, L. G. (1986). *A standard predictive index of human response to the thermal environment*. ASHRAE Transactions, 92(part 2B), 709-731.

Gao, J., Wang, Y., & Wargocki, P. (2015). *Comparative Analysis of Modified PMV Models and SET Models to Predict Thermal Comfort*. Building and Environment, 92, 200-208.

Givoni, B. (1992). *Comfort, climate analysis and building design guidelines. Energy and Buildings,* 18, 11-23. doi:10.1016/0378-7788(92)90047-K

Homod, R. Z., & Shuayb, K. S. (2014). *Energy saving by integrated control of natural ventilation and HVAC systems using model guide for comparison*. Renewable Energy, 71, 639-650.

Hu, J., & Kang, P. (2014). *Model predictive control strategies for building with mixed-mode cooling. Building and Environment*, 71, 233-244.

Jay, A., Brun, A., Thebault, S., & Foucquier, A. (2020). *Dynamic infiltration airflow rate measurement thanks to tracer gas method: a case study at a dwelling scale*. In 15th ROOMVENT Conference, Torino.

Jay, A., Fares, H., Rabouille, M., Oberle, P., Thebault, S., Challansonnex, A., & Anger, J. (2021). *Evaluation of the intrinsic thermal performance of an envelope in the summer period.* Journal of Physics: Conference Series, 2069(1), 012093.

Johnston, D., Miles-Shenton, D., Farmer, D., & Wingfield, J. (2013). *Whole House Heat Loss Test Method* (Coheating).

Kim, J. T., Lim, J. H., Cho, S. H., & Yun, G. Y. (2015). *Development of the Adaptive PMV Model for Improving Prediction Performances*. Energy and Buildings, 98, 100-105.

Marc, O., Anies, G., Lucas, F., & Castaing-Lasvignottes, J. (2012). *Assessing performance and controlling operating conditions of a solar driven absorption chiller using simplified numerical models.* Solar Energy, 86, 258-269.

Payet, M., David, M., Lauret, P., Amayri, M., Ploix, S., & Garde, F. (2022). *Modelling of Occupant Behaviour in Non-Residential Mixed-Mode Buildings: The Distinctive Features of Tropical Climates.* Energy and Buildings, 259, 111895.

Rodriguez, C. M., & D'Alessandro, M. (2019). *Indoor Thermal Comfort Review: The Tropics as the Next Frontier.* Urban Climate, 29, 100488.

Thébault, S. (2017). *Contribution à l'évaluation in situ des performances d'isolation thermique de l'enveloppe des bâtiments (Doctoral dissertation).* INSA de Lyon.

Thébault, S., & Bouchié, R. (2018). *Refinement of the ISABELE method regarding uncertainty quantification and thermal dynamics modeling*. Energy and Buildings, 178, 182-205.

Thébault, S., & Bouchié, R. (2015). *Estimating infiltration losses for in-situ measurements of the building envelope thermal performance*. Energy Procedia, 78, 1756-1761.

Vellei, M., Herrera, M., Fosas, D., & Natarajan, S. (2017). *The Influence of Relative Humidity on Adaptive Thermal Comfort.* Building and Environment, 124, 171-185.

Vellei, M., & Le Dréau, J. (2020). *On the Prediction of Dynamic Thermal Comfort under Uniform Environments.* Conference WINDSOR, 17, 1-6.

Wissler, E. H. (2018). *Human temperature control: A quantitative approach (Doctoral dissertation).* The University of Texas at Austin, Department of Chemical Engineering.

Zhai, Z. J., & H. J. (2011). *Assessment of natural and hybrid ventilation models in whole-building energy simulations*. Energy and Buildings, 43, 2251-2261.