ABSTRACT

Hu, Jianjun. Ph.D., Purdue University, August 2014. A Study of Model-Predictive Control Strategies for Buildings with Mixed-Mode Cooling.
Major Professor: Panagiota Karava.

As awareness about the energy consumption and environmental impact of buildings grows, high-performance building designs that could directly benefit from the advancement of control strategies are gaining significant attention. Building technologies such as thermally activated building systems, thermal storage, mixed-mode cooling systems, etc., take advantage of unique building and weather characteristics such as local heat sources/sinks, and dynamic effects related to variability in occupancy and environmental conditions. Within this context, mixed-mode (MM) cooling is a hybrid approach for space conditioning, employing natural ventilation, where the flow is driven by wind or thermal buoyancy forces sometimes assisted by a fan, and mechanical systems, along with smart switching to minimize building energy use and maintain occupant thermal comfort. However, the control strategies used in current practice usually involve a series of simple heuristics, which may lead to increased operating costs or occupant discomfort since they are not optimized for the local climate and specific building design. Model-based predictive control (MPC) is a promising alternative, particularly suitable for slow response dynamic systems, such as MM buildings with high levels of exposed thermal mass. It solves and implements a sequence of optimal control problems, within a future time horizon, with the most up-to-date information on inputs and environmental disturbances for the dynamic system model.

The overall objective of this research is to (a) develop control-oriented dynamic models of buildings with high performance mixed-mode features, both time-variant and time-invariant, based on first principles (forward) as well as gray- and black-box system identification methods that capture the relevant MM building dynamics and mode

switching behavior and are computationally efficient for subsequent use in control operations; (b) develop an efficient optimization approach suitable for binary control variables (c) formulate offline and real-time deterministic MPC prototypes and demonstrate their performance bounds in terms of energy consumption and comfort maintenance in multi-zone MM buildings. To this end, the study developed a detailed dynamic model of a multi-zone building optimally designed for natural ventilation, with high levels of exposed thermal mass and an atrium that assists buoyancy-driven flows, by using the finite difference method and integrating the thermal dynamics with a multi-zone airflow network model. The model is then used within an offline deterministic MPC with Particle Swarm Optimization (PSO) as optimizer. Performance bounds (energy consumption and thermal comfort) of predictive controllers are evaluated in comparison with heuristic and baseline night setback control. The results show that MPC can significantly reduce the cooling requirements compared to baseline night setback control while maintaining the operative temperature during the occupied period within acceptable limits. On the contrary, the heuristic control strategies for cooling mode switching, based on simple heuristics for the outdoor conditions, create an increased risk of overcooling with lower thermal comfort acceptability. The optimal control sequences with MPC strategy demonstrate intelligent mode switching with superior overall performance. Results also show that the coordinated control shading devices can further increase the energy savings.

The study then extends the physical-based detailed model to forward linear time-variant state-space (LTV-SS) model which provides clarity and insight about the dynamics of MM building operation. The LTV-SS model is validated using measured data from a test-building with mixed-mode cooling under different operational modes, located at Purdue's Architectural Engineering Labs. The validated LTV-SS model is further reduced to a 4^{th}-order model by retaining two states for each controlled zone, representing the air temperature of the zone and the area-weighted mean internal surface temperature. A key feature of the model is the time-variant thermal resistances, which are calculated using an airflow network model. The RMSE for the south and north zone air temperature prediction is 0.58 °C and 0.36 °C respectively (mode 2). Further on, with the detailed forward LTV-SS model simulation results as training dataset, a linear time-invariant state-space model (LTI-SS) is identified with the sub-space state-space method. The LTI-SS model can capture the switching behavior of a real multi-zone MM building with high performance features, with RMSE for the air temperature of 0.64 ºC, and it is computationally efficient for implementation in real controllers due to its independence on airflow network.

An efficient optimization approach is then developed for MM buildings that can be implemented for the binary control of window opening schedules for mode switching. It is based on multi-level optimization topology with progressive refinement and branch-and-bound decision trimming strategy, combined with an effective method for the decision space reduction using heuristic rules. The predictive control with the optimization method show the same performance, in terms of energy savings and thermal comfort maintenance, with the PSO optimization method with significantly lower computing resources (e.g. reduced a 48 hours optimization to 2 hours). Finally, the developed optimization and modeling approaches, are used for formulating a real-time MPC framework, in which a solar prediction model and state initialization method are also proposed. The formulated control framework is implemented and demonstrated in the MM lab building with cooling.

In summary, the mixed-mode cooling strategies developed in the present study, with the improved predictive control can result in significant reduction of building energy consumption and improvement of occupant comfort. A five-month simulation study for a test-building located in West Lafayette, IN showed 40.7% energy savings when switching schedules are made based on heuristics and 31.0% when a predictive control strategy is used. However, the heuristic strategy would lead to a total deviation of operative temperature of 459.7 ºC from the desired range while the corresponding number for the predictive strategy was 45.2 ºC. A similar two-month simulation study for a generic section of a building located in Montreal, Canada showed 54.1% savings with heuristic and 38.6% with predictive control with total operative temperature deviations from the desired range 235 ºC and 35 ºC respectively. The control-oriented modeling approaches, efficient optimization algorithms, and prototypes (numerical and experimental) of predictive control strategies developed in this study facilitate future implementation of MPC strategies in real MM buildings and contribute to the adoption of innovative energy management concepts in engineering practice.