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Optimal exergy control of building HVAC system

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HIGHLIGHTS

- Formulate and validate energy and exergy models of a test-bed building.
- Introduces a new approach for building energy controls.
- Characterize exergy destruction for analysis and design of optimal controllers.
- Compare energy-based and exergy-based MPC controllers for HVAC systems.

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ABSTRACT

Exergy or availability is an accurate metric related to quality of energy and it is used to determine sustainability of an energy system. Exergy has been extensively used to evaluate efficiency of energy systems and energy conversion processes. An exergy model for a building is presented in this study. In this paper, exergy destruction, which indicates the loss of work potential, is formulated as a function of physical parameters of the building model and environment. To minimize exergy destruction in an Heating, Ventilation and Air-Conditioning (HVAC) system, we develop model predictive control (MPC) technique using the exergy model. Comparing to a traditional on–off controller for the building, the proposed exergy-based MPC (XMPC) reduces the exergy destruction and energy consumption up to 22% and 36%, respectively. Simulation results also indicate the advantage of XMPC over conventional energy-based MPC (EMPC). The results show that XMPC reduces exergy destruction by 4% compared to EMPC as well as saving 12% more energy.

1. Introduction

Exergy is described as the maximum theoretically available energy that can do work with respect to a given state via a reversible process [1]. A thermodynamic system's potential to do work increases as it moves away from its equilibrium (e.g., a higher temperature difference with the environment [2]). Conversely, there is no work potential if a system is at the thermodynamic equilibrium with its environment and the exergy of the system in that condition is zero. The First Law of Thermodynamics (FLT) is related to energy conservation. However, FLT does not provide insight about the theoretical efficiency limit due to irreversibility/deficiency in the processes and the direction of natural processes. While the Second Law of Thermodynamics (SLT) concerns entropy generation and irreversibilities which cause deficiency and energy waste in a system. SLT asserts that a spontaneous process or energy transfer occurs toward entropy increase. According to SLT, energy has quality and quantity. The quality of energy decreases in natural processes [3]. Exergy-wise controls provide a means to maximize the usage of energy quantity and minimize degradation of energy quality during a controlled process. Exergy is based on the First and Second Laws of Thermodynamics and unlike energy, it is not conserved. Exergy models the amount of useful energy with which a system has to work, hence, compared to energy, exergy is a more appropriate metric to analyze power systems.

Heating, ventilation, and air conditioning (HVAC) accounts for more than 50% of energy demand in buildings [4]. HVAC processes occur close to the environment temperature and therefore are considered as low quality energy demands. However, these demands are mostly granted with high quality energy (high exergy) sources such as electricity from grid which itself is mainly obtained from very high exergy sources such as fossil fuels. Thus, it is of a great importance to address low exergy demand (e.g., HVAC demands) with low exergy sources such as renewable energy sources

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Nomenclature

$\alpha_{i,j}$	absorption coefficient of the wall between room i & j (–)
$A^{w}_{i,j}$	area between room ith & room jth (m^2)
A^{win}_{k}	total area of window between room i and surrounding room k (m^2)
$c_{p_{avg}}$	average specific heat capacity at constant pressure (kJ/kg K)
$c_{v_{avg}}$	average specific heat capacity at constant volume (kJ/kg K)
COP	coefficient of performance (–)
C^{r}_{i}	heat capacity of the ith room (kJ/K)
$C^{w}_{i,j}$	heat capacity of wall between room i & j (kJ/K)
$\underline{\epsilon}$	lower slack variables vector (K)
$\overline{\epsilon}$	upper slack variables vector (K)
gz	specific gravitational potential energy (kJ/kg)
h	enthalpy of the fluid (kJ/kg K)
h_0	dead-state enthalpy of the fluid (kJ/kg K)
I_e	energy index (kW h)
κ	fan coefficient (W s^3 kg^{-3})
m^{room}_{i}	mass of the air inside room i (kJ)
$\dot{m}^{r}_{i}$	air mass flow into or out to the room i (kg/s)
N	prediction time horizon (–)
$\mathcal{N}^{r}_{i}$	set of all nodes surrounding room i (–)
$\mathcal{N}^{w}_{i,j}$	set of all neighboring nodes to node $w_{i,j}$ (–)
$\pi_{i,j}$	window identifier (–)
P_c	cooling power (W)
P_h	heating power (W)
P_f	fan power (W)
$\dot{Q}^{rad}_{i}$	radiative heat flux density on wall (i,j) (W/m^2)
$\dot{Q}^{int}_{i}$	internal heat generation in room i (W)
$\dot{Q}^{H.T.,k}_{i}$	rate of heat transfer to room i (W)
ρ_{en}	comfort penalty for EMPC (kW h/K)
ρ_{ex}	comfort penalty for XMPC (kW h/K)
$r_{i,j}$	wall identifier (–)
R	gas constant (kJ/kg K)
$R^{w}_{i,j}$	thermal resistance between the centerline of wall and the side of the wall (K/W)
$R^{win}_{i,j}$	thermal resistance of window between room i & j (K/W)
ψ	specific flow exergy (kJ/kg)
s	entropy of the fluid (kJ/kg K)
s_0	dead-state entropy of the fluid (kJ/kg K)
T_c	cooling temperature (°C)
T_h	heating temperature (°C)
T_0	reference air temperature (°C)
T^{s}_{i}	supply air temperature of the ith room (°C)
T^{r}_{i}	temperature of ith room (°C)
T^{r}_{j}	temperature of jth room neighboring room i (°C)
$T^{w}_{i,j}$	temperature of the wall between room i and j (°C)
U_t	vector of control inputs (°C)
$\underline{\mathcal{U}}$	minimum value for control input (°C)
$\overline{\mathcal{U}}$	maximum value for control input (°C)
$\delta\underline{\mathcal{U}}$	lower limit on rate of change of supply air temperature (°C)
$\delta\overline{\mathcal{U}}$	upper limit on rate of change of supply air temperature (°C)
v	specific volume (m^3/kg)
$\frac{V^2}{2}$	specific kinetic energy of the fluid (kJ/kg)
$\dot{W}^{r}_{i}$	rate of exergy transfer by work (W)
$\dot{X}^{r}_{dest_i}$	rate of exergy destruction in ith room (W)
$\dot{X}^{H.T.,r}_{i}$	total exergy transfer by the heat transfer (W)

produced by solar panels. HVAC systems can be operated in low exergy fashion by applying exergy-aware control algorithm which reduces irreversibilities in various energy subsystems such as thermal, mechanical and electrical that leads to less exergy destruction, increasing the overall exergy efficiency of the system. In other words, systems can be operated with less irreversibility and as a result, system operation will be more energy efficient and more sustainable.

There are various categories of studies on exergy analysis of energy systems. For building HVAC systems, a great number of studies have been performed for exergy analysis [5–13]. For instance, in [5] a comparison between four different heating systems is provided and exergy efficiency of the systems are evaluated. In [7], authors present energy and exergy analyses of liquid natural gas (LNG) conventional boiler, LNG condensing boiler and an air source heat pump (ASHP). The energy efficiency values were found to be 8.69% for LNG condensing boiler and 80.9% for ASHP, respectively. Most concentration of these studies are on system assessment based on the First and the Second Laws of Thermodynamics and these studies do not provide control techniques to enhance the HVAC system efficiency. In recent years, use of low exergy (LowEx) system such as heat-pumps and solar collectors have spurred great interests in HVAC studies for green buildings. LowEx system and its applications have been studied before in [14–19]. For instance, in [15] LowEx system implementation is presented. Their experimental result show that using LowEx system can drastically increase HVAC system performance. In [19], it is shown that HVAC systems are more exergy efficient if LowEx energy sources are used. Since conventional HVAC systems use high-exergy energy sources, they have not been designed or operated as exergy efficient systems. This paper proposes a control strategy for this problem.

As reported in [20–24], MPC techniques compared to the existing rule-based HVAC controllers offer potential energy saving up to 16–41% for building HVAC. Advantages of MPC for building energy control are discussed in details in [22–31]. Authors in [32,33] reported results of MPC implementation on a real building and discuss its advantages and energy savings. Thus, MPC is also used for the HVAC control framework in this study. All the previous studies [22–31] for building HVAC controls center on incorporating energy analysis for controller design. Our study investigates and compares energy-wise and exergy-wise MPC framework for building HVAC controls.

Given the unprecedented focus on energy efficiency of built environment due to the energy crisis over the last decade, and at the same time, increasing penetration of renewable energy resources, controller design algorithms for building HVAC systems with exergy considerations is crucial. Smart control algorithms enable us to reduce exergy destruction, energy consumption and greenhouse gas emissions of buildings. For instance, exergy loss has been defined as the cost function of a supervisory control system in [34]. To minimize exergy loss, the controller makes accurate decisions based on energy source types (fossils, renewables, nuclear, and hydro-power). The authors in [34] made a comparison between exergy objective function with the *price* and the *carbon emission* objective functions. Their results show economical benefits of carefully managing exergy. In [35,36] an optimal controller is developed to minimize exergy destruction for a vapor-compression cycle (VCC). Their experimental results in [35,36] show that using exergy destruction as the objective function improves performance and