Guest Editorial: Special Issue on Artificial Intelligence in Thermal Engineering Systems

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Abstract

The special issue "AI in Thermal Engineering" covers the most recent studies with a focus on the applications of artificial intelligence (AI) technologies in thermal engineering systems. The overall aim is to report the latest advances of research and development, discuss the pros and cons, and explore the future perspectives on the synergy of AI and thermal engineering. Articles reporting original research contributions and critical reviews on adopting AI to address engineering problems of modeling, prediction, control, optimization, performance assessment, diagnosis of thermal engineering devices, components and systems are welcome. Special focus is given to those problems which have not been adequately addressed by adopting traditional methods due to limited knowledge and information, computation efficiency, capability of generalization and adaptation in applications, etc. The targeted engineering systems include energy storage devices, power plants, heat pumps and cooling or refrigeration plants, combined heat and power plants, buildings and district energy systems, renewable and clean energy systems, and other engineering systems involving thermal engineering processes.

The special issue has received over 30 submissions, and a total of 10 technical papers are selected for publication which cover a broad range of applications including building energy systems, thermal power units, vehicles, and heat transfer processes. These papers addressed challenges and research gaps in adopting AI in real applications, such as model development and adaption, model interpretability, data imbalance, missing data imputation, etc.

1. Introduction

The rapid development of state-of-the-art artificial intelligence (AI) technologies has promoted a new research paradigm for thermal engineering systems. Fueled by the increasing volume of real-world data, the AI-based methodologies often require little a priori knowledge of the underlying physics and can learn complex and new relationships among physical parameters for characterizing thermal systems. In recent years, AI technologies, particularly various machine learning algorithms, have been widely adopted in different thermal engineering systems. The present special issue focuses on the following three tracks: AI-based modeling and prediction of thermal engineering systems, AI-based control and optimization of thermal engineering systems, and AI-based assessment of thermal engineering systems.

1.1 AI-based modeling and prediction of thermal engineering systems

Topics in this category include but are not limited to AI-based prediction models, hybrid AI and physics-based modeling methods, spatio-temporal modeling methods, reliable and efficient machine learning model development with incomplete data, model interpretation, model update and continual learning.

Ref. [1] proposed a real-time energy performance benchmarking method for electric vehicle air conditioning systems. An autoencoder based on the long short-term memory (LSTM) network was developed to encode the impact factors of system energy consumptions. In order to monitor the system performance in real-time, a continual learning method termed elastic weight consolidation (EWC) was adopted to update the autoencoder periodically using new operational data. Continual learning is a concept which refers to training a model on multiple tasks sequentially without forgetting the knowledge obtained from previous tasks, and methods adopting this idea can be used to update deep learning models at relatively low computational costs.

Ref. [2] addressed the missing data problem, a typical data quality issue in AI-based modeling. In the paper, the authors discussed two data missing types in building energy data, i.e., random missing and continuous missing, and explored several deep learning methods for missing data imputation. The Building Data Genome 2.0 (BDG2) open dataset with hourly meter readings was used for performance validation. Results showed that, compared with the one-dimensional or two-dimensional convolutional neural network (1D-CNN, 2D-CNN) models, the partial convolution (PConv) model had much lower prediction error for data imputation and could be an effective solution for this problem.

Ref. [3] focused on the feature-level model interpretation of a convolutional neural network (CNN)-based fault detection and diagnosis (FDD) model for chillers. The research adopted a gradient-based method to interpret CNN models, which helps to localize fault-related features of chillers and explain the underlying fault identification process.

Ref. [4] focused on imbalanced data samples, a typical issue in training AI-based FDD models since faulty samples are usually harder to collect than fault-free samples. This paper first converted the time series data of chillers to Gramian angular field (GAF) images, and then applied the conditional variational autoencoder-generative adversarial network (CVAE-GAN) to generate synthetic faulty samples to balance the dataset for training. CVAE-GAN is a fusion algorithm which combines VAE and GAN for generative modeling. A 2D-CNN classification model was then developed in relatively balanced data scenarios for chiller fault diagnosis.

Ref. [5] studied the prediction model of heat transfer deterioration (HTD) for supercritical fluids in upward vertical tubes. Since traditional methods usually lead to overestimation of the heat flux at HTD onset, the paper proposed a new definition of HTD based on multiple factors and used a couple of machine learning methods such as support vector machine (SVM), K-nearest neighbors (KNN), etc. to solve the binary classification problem of HTD and no-HTD.

1.2 AI-based control and optimization of thermal engineering systems

Topics in this category include but are not limited to model predictive control (MPC) using machine learning models, reinforcement learning (RL) for optimal controls, human-system interaction modeling for optimal controls, and edge computing technologies for real-time monitoring and controls.

Ref. [6] is a survey paper that concentrates on design, analysis, and hardware of AI applications in heating, ventilation, and air conditioning (HVAC) systems for the purpose of energy saving. By reviewing more than 1,000 research papers, the authors summarized the case studies of input-output models, MPC, DRL, fuzzy control, and evolutionary algorithms (EA) for HVAC systems. The paper emphasized the importance of hardware upgrades and the integration of software and hardware in the application of AI in HVAC systems.

Ref. [7] compared MPC and RL for optimization of building energy systems, using the performance of a proportional-integrative (PI) controller as the baseline. The building optimization testing (BOPTEST) framework was employed as the virtual test environment. Results showed that, for three RL controllers, namely deep deterministic policy gradient (DDPG), dueling deep Q networks (DDQN), and soft actor critic (SAC), only DDPG can outperform the baseline PI controller in all testing scenarios. Meanwhile, despite the use of a rather simple one-resistance-one-capacitance (1R1C) gray-box model, the MPC controller outperformed both baseline and RL controllers.

Ref. [8] proposed a hierarchical controller for thermal management of fuel cell hybrid electric vehicles. The controller incorporated the DDPG algorithm in RL to optimize the stack efficiency, fuel economy, and temperature tracking performance.

Ref. [9] researched machine learning-based methods for multi-objective optimization problems in the organic Rankine cycle (ORC) of vehicle engines. The paper developed a neural network model of ORC based on simulation data and applied the genetic algorithm to maximize the thermal efficiency and power output.

1.3 AI-based assessment of thermal engineering systems

Topics in this category include but are not limited to AI-based anomaly detection, fault detection and diagnosis (FDD), predictive maintenance, knowledge transfer and other practical applications.

A few articles introduced in Section 1.1 use AI models for performance assessment. Ref. [1] focused on anomaly detection of HVAC systems. The article established Gaussian process regression models to benchmark the energy performance of a large number of vehicle air conditioning systems and then identified systems with abnormal energy consumption. Ref. [3] and Ref. [4] focused on fault detection and diagnosis tasks in HVAC systems using CNN models. Ref. [3] emphasizes on black-box model interpretation, while Ref. [4] focuses on tackling the data imbalance challenge in model development.

Ref. [10] focused on diagnosing the inadequate load output of thermal power units, which is difficult for conventional physics-based models due to its complex unit structures. The paper constructed a multi-label random forest classification model to identify the root cause of inadequate load output, while an improved whale optimization algorithm was proposed to improve model accuracies.

2 Conclusions

AI technologies have proved to be revolutionary in changing the way we think, learn and work in various fields. Despite the rather traditional nature of thermal engineering, AI-empowered methods have gained increasing attentions from both academia and industry due to the wide availability in simulation and real-world data, which opens great opportunities to conduct multi-discipline research for knowledge discovery and application.

This special issue covers novel studies utilizing AI technologies to solve practical problems in thermal engineering systems, ranging from predictive modeling, control optimization to performance assessment.

Leveraging advances in advanced data analytics, AI methods have shown promising results in enhancing modeling accuracies, tackling different data quality challenges, and upgrading control optimization tools. A clear research trend has been observed as in-depth studies are emerging to integrate multiple machine learning paradigms to enhance the applicability of AI-empowered methods, such as interpretable machine learning, generative modeling and reinforcement learning. Meanwhile, it is worth mentioning that existing studies mainly focused on analyzing structured data collected during thermal system operations, yet unstructured data, such as texts and images, are also available for analysis and calling for more research efforts. We appreciate the contributions of the authors and believe this special issue can bring valuable insights and useful references for the application of AI technologies in thermal engineering systems.

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