Energy–Performance Trade-off Analysis of Adaptive GRU-Scheduled PID Control for Vapor Pressure Deficit Regulation in Evaporative-Cooled Greenhouses

Natthanan Wanna[1], Kriengkrai Nabudda[3], Suphasit Sitthaphanit[2], and Natakorn Thasnas[1,*]
[1]Department of Electrical and Computer Engineering, Faculty of Science and Engineering, Kasetsart University, Chalermphrakiat Sakon Nakhon Province Campus, Sakon Nakhon 47000, Thailand
[2]Department of Agriculture and Resources, Faculty of Natural Resources and Agro-Industry, Kasetsart University, Chalermphrakiat Sakon Nakhon Province Campus, Sakon Nakhon 47000, Thailand
[3]Department of Industrial Engineering, School of Engineering, King Mongkut's Institute of Technology Ladkrabang (KMITL), Bangkok 10520, Thailand

Corresponding Author Email: natakorn.th@ku.th

Abstract

Vapor pressure deficit (VPD) is a critical microclimate variable governing plant transpiration and water-use efficiency in protected cultivation. Accurate VPD regulation in evaporative-cooled greenhouses remains challenging due to nonlinear temperature–humidity coupling and rapidly varying solar disturbances. This study presents an energy–performance trade-off analysis of five greenhouse control strategies, with emphasis on a proposed adaptive GRU-scheduled PID controller implemented on a Siemens S7-1200 programmable logic controller and experimentally evaluated in a full-scale evaporative greenhouse in northeastern Thailand. To unify regulation quality and energy consumption into a single metric, a novel Regulation Quality-per-Energy (RQE) index is introduced, defined as the inverse of RMSE normalized by daily energy consumption. Experimental results demonstrate that the proposed GRU controller achieves the best VPD tracking accuracy (RMSE = 20.81 Pa, ITAE = 2,406 kPa·min) and the highest RQE index (2.40) at 20.02 kWh/day — a 74.19% reduction in energy relative to full-capacity evaporative cooling (77.58 kWh/day, RMSE = 448.17 Pa). Annual projections indicate electricity cost savings of approximately 84,038 THB and CO_2 avoidance of 9.98 tonnes per greenhouse per year versus full-capacity operation. These findings establish adaptive gain scheduling as a viable pathway to simultaneously improving regulation quality and energy sustainability in precision greenhouse agriculture, supporting Bio-Circular Green Economy objectives.

Keyword: vapor pressure deficit, greenhouse climate control, GRU-scheduled PID, energy efficiency, precision agriculture