Energy and Comfort Evaluation of Air-source and Wall-embedded Heat Pumps for Heating Applications

Abstract

The adoption of smart home technologies, particularly smart and programmable thermostats, is growing rapidly in residential buildings. The 2020 Residential Energy Consumption Survey reports that 52% of U.S. households now use these advanced thermostats. The emergence of smart, connected thermostats with data collection capabilities has facilitated seamless operation and provided valuable data on occupant interactions, spurring numerous studies into how people adjust thermostat setpoints for comfort and the factors influencing these preferences. Understanding human interactions with thermostats and setpoint preferences is essential, as these behaviors directly impact the operation of heating and cooling systems, affecting both energy use and indoor thermal conditions. Although many studies have focused on occupant setpoint preferences, there remains a significant gap in research addressing differences in setpoint behaviors across various comfort delivery systems, especially differnt heating systems(e.g., heat pumps, gas furnaces) in cold climates. This study aims to investigate how the operational characteristics of different comfort delivery systems in cold weather influence occupants' thermostat adjustment behaviors, identify the limitations of current heat pump systems and develop a novel wall-embedded micro heat pump radiant heating system that enhances comfort and reduces energy use, contributing to the electrification of residential buildings.

This study first presents a field study conducted in 30 homes within a newly built residential community to collect data on occupants' thermostat adjustments under two different operation modes: 1) a baseline mode featuring a heat pump paired with an auxiliary heater controlled by default thermostat heuristic rules, and 2) a comparison mode where the auxiliary heater was activated to provide the majority of heating. The findings showed that 8 out of 13 units preferred lower setpoints in the comparison mode, where higher supply air temperatures were utilized. Four distinct setpoint-increasing behaviors were identified, contributing to the observed setpoint differences between the two modes. Notably, two of these behaviors were closely linked to the operational characteristics of heat pumps in cold weather, specifically cases of insufficient and sufficient HP capacity.

To further explore the differences in setpoint preferences and the motivations behind setpoint adjustments, two case studies were designed, and 32 human subject experiments were conducted in a controlled laboratory (Human Building Interaction Laboratory). The first case, with a single-stage heat pump and auxiliary heater, replicated the operational characteristics observed in the field study. The second case, using a variable-speed heat pump with enhanced comfort features, aimed to investigate participants' comfort preferences and provide insights for future heat pump design improvements. According to the thermal comfort survey results, 19 out of 32 participants increased their setpoints in the single-stage heat pump case, even though the heat pump had sufficient capacity to warm the indoor space. Cold air movement and indoor temperature fluctuations due to the heat pump cycling on/off were the main reasons participants reported increasing their setpoints in this case. In contrast, participants felt more comfortable with the variable-speed heat pump in the laboratory study, attributing their comfort to stable indoor temperatures and the absence of cold air movement.

Finally, a novel wall-embedded micro heat pump (WEMHP) was developed to provide local comfort and could contribute to reducing energy consumption and electrification of residential buildings. This new distributed comfort delivery approach has several distinct advantages compared to alternatives: (1) A WEMHP eliminates the need for a secondary water loop and does not require separate indoor and outdoor units. Instead, a WEMHP unit operating in heating mode directly absorbs heat through an embedded heat exchanger (evaporator) at the outside wall surface and then conditions the indoor space using an embedded heat exchanger (condenser) at the indoor surface. (2) This packaged solution eliminates the need for extensive HVAC installation and on-site refrigerant charging. (3) The interior surface temperature of the exterior wall section empowered by the micro heat pump is independently controlled, allowing for distributed space conditioning and delivery of radiant heating to meet diverse occupant needs in different zones. The system performance was studied thoroughly based on energy simulation and experimental comfort study. Moreover, a prototype WEMHP was designed, assembled, and tested in a laboratory environment as a proof-of-concept demonstration. The test results demonstrated that the heating capacity under condition H1 reached around 200 W at a compressor speed of 4000 RPM with a COP of 1.67. Additionally, the system exhibited a fast thermal response, with a time constant τ_{63} (the time it takes for the surface temperature to reach 63% of the difference between its final and initial values) of less than 0.5 hours and a τ_{95} of approximately 1.5 hours.