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Experimental and analytical investigation of hydronic system retrofits in an urban high-rise mixed use building

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ABSTRACT

As the size of buildings and demands on large centralized heating and cooling systems increases concurrent with rapid worldwide urbanization, the energy impact of hydronic distribution systems will become increasingly important in reducing greenhouse gas emissions. Further, in the U.S., the growth in multi-family buildings and the share of residential units in large multifamily buildings is far outpacing single-family construction. This paper describes a study of the pumping energy requirements of an urban 23-story mixed-use, primarily multifamily residential building before and after a suite of energy conservation measures. The retrofit focused on waterside technologies: Variable frequency drives (VFDs), constant and variable speed pumps, and pressure-independent control valves. In the original building, the central pumping equipment was found to be responsible for 55% of total annual owner-metered electricity usage and 29% of all annual owner-paid utility bills. Using extensive in-situ monitoring and analytical models developed for this effort, the full retrofit was computed to achieve a 41% reduction in annual central pumping electricity, representing an annual savings of 12% of all owner-paid energy bills. The most significant energy impact is attributable to the VFDs, and it can be inferred that additional savings could be achieved by installing VFDs on constant speed pumps.

1. Introduction

Buildings account for 41% of total U.S. primary energy usage [1]. Space conditioning (heating and cooling) and domestic hot water (DHW) represent more than 46% of primary energy usage (sometimes referred to as "source" energy) attributable to buildings. Multifamily residential buildings are fast becoming a critical component of this landscape: A 20 billion square feet increase in total U.S. multifamily residential floor area has been projected by 2021 relative to the 2011 building stock, compared to a 4 billion square feet *decrease* in total U.S. single-family residential floor area [2]. The potential complexity of multifamily building mechanical systems is of particular interest as the size of individual buildings increases: In 2014, 48% of all new multifamily residential units in the United States were in buildings that contain at least 50 residential units; 20 years earlier, the equivalent value was 8% [3].

With steam-based space heating systems difficult to deploy in complex structures [4] and not ideal for the heterogeneous loads of mixed building uses, the adoption of more flexible and controllable hot water distribution systems (i.e. hydronic systems) requires pumps to circulate the water [5]. Chilled water can also be similarly distributed to thermal zones from central mechanical refrigeration plants in large buildings [6].

With rapid worldwide urbanization [7], and the attractiveness and potential benefits of higher density living [8], new construction in cities is increasingly tall multifamily and mixed use buildings. According to data available from New York City [9], 49% of total citywide building floor area is in multifamily residential and mixed use buildings; 18% of total citywide building floor area is in high-rise[1] multifamily and mixed use buildings. In Manhattan, a high-density area and possible harbinger of future urban development, 37% of all building floor area is in high-rise multifamily and mixed use buildings.

The energy required to operate pumps across the building stock and for individual building types is difficult to estimate; one study commissioned by the U.S. Department of Energy estimated that 3%

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[1] Throughout this paper, seven stories is used as the threshold for a high-rise building based on the NFPA Life Safety Code definition as a "building with an occupied floor located more than 75 feet above the lowest level of fire department vehicle access" [46]. NFPA itself has used the seven story assumption in publication [47].

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of all U.S. HVAC energy consumption is used by pumps [10,11], but this likely significantly underestimates the requirements for large buildings and hydronic systems. A report by the U.S. Department of Energy's "Building America" program identified determining the electricity requirements for pumping in hydronic heating systems as a current research gap [12].

System complexity, the hydraulic response to highly variable loads, efficiency of individual pieces of equipment, interrelated effects of individual system components, and the tendency to apply large factors of safety in the design phase (i.e. oversizing equipment) all provide challenges to improving system energy performance, particularly in existing buildings [13,14].

This paper examines the energy effects of a suite of waterside retrofits in an urban high-rise mixed use (primarily residential) building's heating, cooling and DHW systems through analysis of extensive monitoring time series data. The paper first provides a review of recent research into the types of systems and equipment studied (Section 2). Section 3 describes the methodology, including study building description, experimental setup and analytical approach. Section 4 presents the pertinent results, and Section 5 discusses the implications of the paper's findings. In Section 6, conclusions from the current effort are offered, as well as needs for further research.

2. Background

Given publication space limitations, a detailed review of the systems and technologies investigated is not possible here; however, we provide a summary of research relevant to the effects studied.

2.1. Hydronic systems

Where dynamic hydronic systems for actual buildings have been analyzed, they have been limited to simple single-family residential construction [15] or models that have been evaluated without experimental validation [16,17]. The underlying theories of pipe network flow and pressure behavior and methods for solving them are well established [18]. These approaches have been extended to numerical models to solve the hydraulic equations associated with thermal hydronic networks as the system responds to loads changes [19–21]. A more integrated approach has also been studied in a laboratory setting in which the heat exchanger network acts as an emulator in a "hardware-in-the-loop" simulation, responding to the model and allowing for more tuning [22]. These studies have shown good agreement between predicted and actual performance; however, they have been limited to simplified laboratory heat exchanger networks for validation. There is a clear research gap for the evaluation of hydronic systems for actual large buildings.

2.2. Centrifugal pumps

The operating point of a hydronic system, defining the differential pressure, Δp, and the water flow rate, $\dot{V}$, is the intersection of the pump curve and the system curve. The pump efficiency, η_p, and to a lesser extent, the motor efficiency, η_m, also depend on this operating point. The system curve changes with load changes; however, the pump curve is fixed for a constant speed system.

The hydraulic power (commonly "water horsepower"), P_h, the pump power at the shaft (commonly "brake horsepower"), P_p, and the motor electric power, P_m, are related by:

$$P_m = \frac{P_p}{\eta_m} = \frac{P_h}{\eta_m \eta_p} = \frac{\dot{V} \Delta p}{\eta_m \eta_p} \tag{1}$$

This paper is primarily concerned with the electricity required to drive pumps. Selecting a pump for a new building requires estimating the pressure drop in the system under full load conditions. In estimating the zonal heating and cooling loads, a safety factor of at least 10% is typically applied, leading to larger terminal units [23]. Further, a building with many terminal units and/or proportional control valves is unlikely to ever be at the design load. Another safety factor is applied to the pressure drop after estimating losses at the design flow rate [24]. These safety factors and overestimates are compounded when determining the pump power required. The pump may be further oversized due to nominal equipment sizes and a pump size factor of safety. The result can be a far larger pump than needed for the actual system [25,26].

Pump oversizing can have significant impacts on energy performance throughout the hydronic system, including excessive pump motor electricity draw and low power factor, reduced heat transfer effectiveness of heating and cooling coils, and lower chiller efficiency [26,27].

Reducing the speed of the pump shaft can reduce the flow rate. The potential energy savings from this approach are exponential due to the pump affinity laws, relationships among water flow rate, $\dot{V}$, differential pressure, Δp, and pump power, P_p, at different rotational speeds, n_1 and n_2,:

$$\frac{\dot{V}_2}{\dot{V}_1} = \frac{n_2}{n_1}, \frac{\Delta p_2}{\Delta p_1} = (\frac{n_2}{n_1})^2, \frac{P_{p,2}}{P_{p,1}} = (\frac{n_2}{n_1})^3 \tag{2}$$

The affinity laws rely on the assumption that the pump efficiency does not change with speed and are generally accurate at the speeds seen in centrifugal pumps in building applications [28,29].

2.3. Variable frequency drives

The most common method of varying the speed of a pump is a variable frequency drive (VFD), which reduces the frequency of the electricity supply to an AC motor. The energy savings from VFDs can be overestimated [30], primarily because a small amount of electricity is needed to operate the VFD and the motor efficiency can decrease at reduced motor load/speed [31].

Previous studies of VFDs that identify deviations from the affinity laws focus on control schemes in existing variable flow systems rather than system design effects [17,32,33]. VFDs are typically controlled to maintain a differential pressure set point at some point hydraulically distant from the central plant equipment or across the main supply and return lines of the distribution loop, though more complex control strategies have been investigated to minimize energy usage or costs [32,34].

The benefits of VFDs for motors have been well documented for a wide range of applications [35], including several pumping applications: building heating and cooling systems [36,37], distributed heating systems [38] and industrial applications [39].

2.4. Flow control valves

Many types of valves are available for hydronic systems that offer a range of responsiveness to changes in system state and of control by building operators and BMS [40]. Flows through basic venturi valves and standard calibrated balancing valves can fluctuate widely during system operation. As loads fluctuate throughout a building, increased local pressures result in corresponding local flow increases. Pressure dependent control valves (PDCVs) can be adjusted (e.g. in response to a thermostatic sensor and control), but still respond with excessive flow to increased system pressure [41].

Pressure independent control valves (PICVs) offer the ability to control the flow rate set point through the BMS or local temperature sensor-control [42]. While manufacturers perform laboratory tests to determine valve accuracy and hysteresis effects, in-building energy effects of PICVs have not been studied.