Energy & Buildings 179 (2018) 183–199

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enbuild

Quantifying energy losses in hot water reheat systems

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ARTICLE INFO

Article history:
Received 28 June 2018
Revised 5 September 2018
Accepted 15 September 2018
Available online 19 September 2018

Keywords:
Hot water reheat
Boiler
Distribution system efficiency
Virtual meter
Energy efficiency
Variable air volume

ABSTRACT

We developed a new method to estimate useful versus wasted hot water reheat energy using data obtained from typically installed instrumentation that applies to all pressure independent VAV terminal units with discharge air temperature sensors. We evaluated the method using a year of 1 min interval data for a 11,000 m^2 building with 98 terminal reheat units, and found a 14% upper bound for the uncertainty associated with this method. We found that just 21% of gas energy is converted to useful reheat energy in this building. The distribution losses alone were 44% of the heat output from the boiler. The results raise questions regarding the tradeoffs between hot water heating systems, which have significant distribution losses, and electric heating systems, which effectively have zero distribution losses. In this building, and likely many others, an electric reheat system supplied by a small photovoltaic panel system would have a lower operating energy cost and a lower initial cost than the hot water reheat system. Further investigations using this method will be relevant to designers and standards developers in deciding between electric and hot-water reheat, particularly for modern designs using dual-maximum controls and low minimum airflow setpoints.

1. Introduction

Where a central heating ventilation and air conditioning (HVAC) system supplies multiple zones with the same temperature air, heating coils are needed at the terminal units (i.e. at the zone or room level) in zones that may require heating when there is a demand for cooling elsewhere in the building. An air handling unit (AHU) single-duct system serving multiple zones with variable air volume (VAV) terminal units is a very common type of HVAC system in commercial buildings. Each terminal unit has a damper to control airflow to meet ventilation air requirements and so that it can increase airflow to provide cooling as needed up to its design maximum flow rate. In all but the warmest climates, perimeter zones require heating coils at the terminal units. However, heating coils are also often needed in interior zones to ensure that these zones are not overcooled when supplying (typically cool) ventilation air. For example, when the supply air leaving the AHU must be quite cool to meet a need for cooling in the building (e.g. a west facing zone, operating at maximum air flow), this supply air temperature may be too low for other (e.g. interior) zones served by that AHU. These terminal unit heating coils are typically known as 'reheat coils' as there are some times of the year when the AHU has cooled the supply air, only to then 'reheat' it at some terminal units. Either electricity or a hot water distribution system serves as the energy source for these coils. Hot water reheat systems, typically served by a gas-fired boiler, are more widely used in buildings because of lower utility costs than for electric reheat systems. Electric reheat is even prohibited in some codes and standards (such as California Title 24 [1]).

For context, Zhang et al. [2] recently concluded a large study of distribution losses for a conceptually similar type of system: open-loop centralized domestic hot water recirculation systems fed by natural gas boilers. The results showed that the delivered hot water energy in 28 different buildings averaged just 35% of the source gas energy consumption [2], that is, there was a 65% loss in the system, due in equal part to distribution losses and losses at heating equipment. There are numerous studies [3–13] of heat transfer and demand within open-loop domestic hot water systems for a range of different applications in both commercial and residential buildings. The overall system efficiency and distribution system losses vary very widely depending on design and application. Chapter 50 of the ASHRAE handbook of applications [14] summarizes this well as "Energy losses from hot-water distribution systems usually amount to *at least* 10% to 20% of total hot-water system energy use in most potable water-heating systems [3], and are

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https://doi.org/10.1016/j.enbuild.2018.09.020
0378-7788/

often as high as 50%; losses of over 90% have been found in some installations [15]". This includes both heat lost from the distribution system, as well as water and heat wasted at the fixture as the user waits for water to reach a usable temperature. These findings show that the overall system efficiency is far lower than expected based on idealized analysis of these systems.

In comparison, though there is no water waste in a closed-loop reheat system, many losses are similar to open loop domestic hot water systems. In a closed-loop hot water system used for primary heating, where the majority of the building is operating in heating mode, these losses are of less concern as long as the losses occur within the building envelope. Though they may cause control problems (e.g. overheating in some zones), the losses still contribute to heating the building overall. In contrast, for reheat systems, the demand for heat is typically only from a relatively small number of zones in the building, under conditions that vary widely based on the time of day, supply air temperature, heat load in the zone, minimum airflow rates, heat transfer through the envelope, etc. Reheat demand often occurs during times of the day and year in which the majority of the zones in the building require cooling, or in large buildings where the interior zones always require cooling independent of outdoor weather conditions. In this case, the losses will also be a significant component of overall hot water system efficiency.

Lastly, recently developed control strategies used to improve the energy efficiency of VAV systems, such as those described and demonstrated in [16–20] and recently formalized in ASHRAE Guideline 36 [21], successfully avoid most unnecessary reheat energy. These strategies reduce the minimum airflow setpoint at the VAV terminal unit to a more appropriate level. Historically, designers have defined this as a fixed percentage of the design maximum airflow, typically 30%, or often even higher (e.g. 50%) for VAV terminal units with reheat coils that use single-maximum control logic.[1] Using dual-maximum control logic [18] or time-averaged ventilation [20] allows the minimum to be set to the correct value—the design ventilation airflow requirement for the zone.[2] Many of the heating system losses described above are constant and do not vary with the need for reheat in the building. Thus, they become proportionally more significant when the overall useful reheat demand decreases.

In this paper we focused on closed-loop systems serving reheat coils at variable air volume (VAV) terminal units, commonly known as 'VAV boxes'. We performed a thorough literature review of likely sources of publications on this topic and were unable to find prior studies that analyzed this specific case. The energy wasted within these systems occurs due to a number of factors:

- Heat lost through insulated and uninsulated piping and fixtures, both during flow conditions and when non-flowing water reaches steady state with the surrounding environment. Hiller [3] describes these losses in detail and illustrates them using a number of example calculations.
- Heat lost by passing valves unnecessarily supplying hot water to a reheat coil, a problem that is unique to the nature of hot-water heating systems of any kind.
- Electrical motor losses serving circulation pumps.
- Boiler combustion, standby and parasitic losses.

In contrast, electric reheat systems have minimal distribution losses, no passing valves, no boiler losses, and lower initial installation costs, but typically have much higher unit energy costs.

We formalized the primary research questions that we wished to answer as: (1) How do we cost-effectively quantify intentional reheat energy use in buildings with hot water reheat systems; (2) What are the distribution losses in a real building; and (3) Under what conditions do the initial cost and operating energy cost tradeoffs favor electric reheat?

2. Case study building

2.1. Description

We performed a case study of a 5 story, 11,000 m^2 office building in the California Bay Area. The Bay Area is a Koppen Csb climate zone (California climate zone 3, ASHRAE climate zone 3C) characterized by dry, warm summers and mild winters. Constructed in 1999, the building is predominately open plan with some enclosed offices and conference rooms along the perimeter, and a central core of services and conference rooms. The window-to-wall-ratio is approximately 0.6 on the first floor and 0.45 on all other floors in most zones, and almost all of these windows are not externally shaded. Approximately 400 people work in the building performing typical administrative tasks and the building is typically occupied from 6 a.m to 5 p.m. The HVAC system in the building recently underwent a complete controls retrofit which has brought it up to current industry best practice, almost identical to the more recently published ASHRAE Guideline 36 [21]. The building has a single-duct, variable air volume (VAV) system, served by two rooftop air handling units with direct expansion (DX) cooling coils and evaporatively cooled condensers. A gas-fired hot water boiler supplies hot water to the terminal (two-row) reheat coils distributed throughout the building, present at most VAV boxes, and those VAV boxes use industry best practice dual-max[3] control sequences [18]. The hot water system has a flow meter and temperature sensors on the supply and return at the boiler, commissioned and calibrated as part of the controls retrofit. The retrofit also included replacing all of the existing reheat coil valves with new, high quality valves. The air handling units also use current industry best-practice supply air temperature and duct static pressure resets based on temperature and pressure requests from the individual zones in the building.

2.2. Zone and AHU information

The building has a total of 144 VAV terminal units (or VAV boxes) among which there are 98 zones with reheat coils, all served by the same closed-loop hot water system. The first step of the analysis investigated the availability and consistency of the data monitored at each VAV reheat box. We logged data from the Building Automation System (BAS) at 1 min intervals from 1st September 2016 to 31st August 2017, i.e. 525,600 records for each monitored variable involved in the analysis. We did not apply any aggregation procedure to the dataset before the analysis. Values monitored at each VAV terminal unit that are relevant for this analysis include: airflow rate, discharge temperature, room air temperature, and reheat valve position. Relevant values monitored for the AHUs include: outside air temperature, supply air temperature and fan speed. The AHUs operated during occupied hours and

[1] Here, the minimum airflow setpoint in deadband must be the same as that which is required to provide the heating capacity for the design heating condition.

[2] This does not reduce the amount of outside 'fresh' air entering the building, as that is controlled at the AHU and remains constant when zone minimum airflow setpoints change. Decreasing the minimum airflow setpoints in the building simply reduces the total amount of air circulating in the building's HVAC system, reducing fan power and wasted reheat energy use, while increasing the fraction of outside air in the supply air leaving the AHU.

[3] Single-maximum control sequences have a single maximum air flow rate at the design cooling condition. The minimum airflow rate in the deadband between heating and cooling modes is often set by the airflow required at the design heating condition. In contrast, dual-maximum control sequences allow a VAV box to control the airflow to a much lower minimum in the deadband, saving a significant amount of reheat and fan energy. See [18] for more detail.