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Daily energy consumption signatures and control charts for air-conditioned buildings

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ABSTRACT

Energy signatures for air conditioning systems can have characteristics which are not seen with heating systems. This paper explains and illustrates some of the characteristics that are specific to air conditioning systems and describes how energy signatures that take account of them can be applied to produce benchmarks, control charts and diagnostic information. It focusses on the use of energy signatures derived from measured daily system energy consumption.

Daily energy signatures can generate more robust energy consumption benchmarks and provide additional insight into unusual energy demand patterns compared to monthly or weekly signatures, albeit requiring slightly more data. In particular, they distinguish between weekday and weekend consumptions. They can be used to generate benchmarks based on standardised annual consumption or standardised annual load factor. In addition they can be used to generate control charts to identify days of unusual consumption for individual systems. More sets of daily energy consumption data are needed to evaluate their diagnostic power.

1. Introduction

The use of energy signatures to characterise heating energy consumption is an established procedure but their application to air conditioning is relatively unfamiliar. One complication is that energy signatures for air conditioning systems can have characteristics which are not seen with heating systems, and the assumptions which hold for heating do not necessarily apply to air conditioning.

This paper explains and illustrates some of these characteristics and describes how these energy signatures can be applied to produce benchmarks, control charts and diagnostic information for air conditioning systems. It focusses on the use of energy signatures derived from measured daily energy consumption of the whole system that is providing cooling into a space. The paper describes procedures and provides an illustrative Case Study to illustrate their application: further work is necessary in the areas of data collection to enable benchmarks to be defined, and practical application to build confidence – or reveal limitations – in the value of the procedures.

Part 1 of the paper refers to previous work, introduces the different forms of energy signatures that may be encountered and illustrates the component elements of a typical air conditioning energy signature using data from a UK office building.

Part 2 addresses the applications of empirical energy signatures: consumption benchmarks, annual load factor benchmarks, control charts and energy efficiency diagnosis.

Part 3 discusses how daily cooling energy signatures may be used to diagnose which aspects of system design or operation would repay further investigation. In general, identification of specific causes of energy wastage will require on-site investigation or the analysis of more detailed consumption data—for example, by remote automatic analysis. (The term “energy wastage” is used to denote energy consumed in excess of a “reasonable minimum” level that is necessary to provide the required service. Clearly what can be considered a “reasonable minimum” depends on the context—replacing equipment may, for example, be considered unreasonable in the short run, but reasonable at some point in the future.)

2. Part 1: Fundamentals

2.1. Energy signatures for air conditioning

2.1.1. Energy signatures

A building energy signature is a plot of the energy consumption of a building versus the mean ambient air temperature, usually on

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a daily basis [1]. It has been widely used as a means of characterising the heating energy consumption of buildings but less commonly for cooling energy consumptions [2–6]. Energy signatures are commonly based on the total energy supplied to a building, usually broken down by fuel type, but they may also be based on sub-metered data for particular end-uses. Energy signatures may be, in principle, based on different time periods: in this paper we focus on signatures based on daily consumptions and daily mean outdoor temperatures. This level of detail provides useful information in a readily assimilated form and requires a limited amount of data and analysis. Much more information, including the identification of specific faults can be extracted from the automated analysis of sub-hourly data [7].

This paper considers the energy consumption of air-conditioning systems used to provide comfort cooling in buildings. While it focusses on the energy used for cooling, the approach is also applicable to measured consumptions of complete air conditioning systems, including energy used by fans and (reverse-cycle) heating. Sub-metering of components at the required level is relatively straightforward in principle, and may be an element of a building energy management system or be carried out remotely.

2.1.2. Forms of energy signatures for air conditioning

Heating energy signatures conventionally take the form of a fixed base consumption plus – above a threshold or base temperature – a linear relationship between consumption and temperature. In practice, there are also day to day variations that are not correlated with outdoor temperature. These may be caused, for example, by variations of solar gain, wind velocity or direction, or of heat gains associated with differing occupancy patterns.

The relatively few published examples of energy signatures for air conditioning identified in Section 2.1.1 show a similar linear trend, notwithstanding that they might be expected to display some curvature due to variations of efficiency or dehumidification load with outside temperature. However, as discussed below, some types of air conditioning systems can be expected to have energy signatures that display discontinuities.

Energy signatures may be applied to the energy consumption of a complete air conditioning system, including mechanical ventilation, or separately to the cooling and air handling subsystems. In the former case there may be consumption by fans or pumps at times when there is no heating or cooling load.

The next part of the paper considers the energy signatures of some of the more common types of air conditioning system. The importance of the different features discussed varies according to climate and building design and use.

2.1.2.1. Reverse-cycle systems. Some air conditioning systems are capable of operating as heat pumps, operating in reverse cycle mode. These systems include packaged systems with and without a ventilation element. In this case the energy signature contains both the cooling (right hand side) and heating (left hand side) aspects of the basic energy signature as shown in Fig. 1. The slopes of the two gradients will be numerically different, corresponding to differences between the cooling energy efficiency ratio and the heating coefficient of performance.

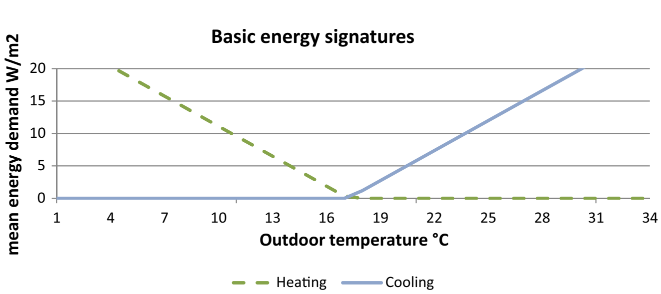

Fig. 1. Principles: Basic energy signatures.

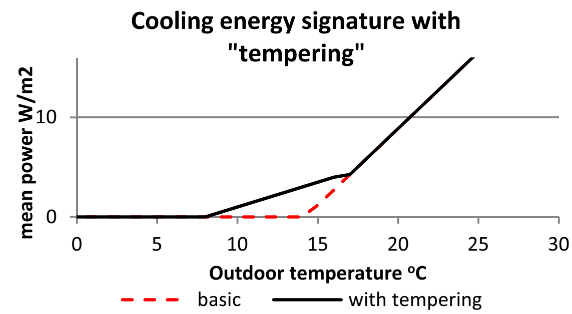

Fig. 2. Principles: Cooling energy signature with tempering.

2.1.2.2. "Tempering" of supply air. Larger air conditioning systems commonly provide a mechanical ventilation service via an air handling subsystem which also provides an element of initial cooling and heating. This supply of cooled air is insufficient to meet the cooling demands under all circumstances and a separate – usually water-based – subsystem provides more localised additional cooling and heating when required.

In order to avoid localised cooler areas and discomfort from cold draughts, the temperature difference between the supply and room air temperatures is usually limited: typically to a temperature difference of between 5 and 8 degrees C see, for example [8]. As a result, there are times when the supply air has to be warmed or "tempered" to meet this supply air temperature comfort requirement. This means that there will be times when the cooling demand in the building could be met in principle by the outdoor air supply but the use of tempered supply air results in a demand on the cooling sub-system. The energy implications of this feature are most significant for combinations of climate and building in which a cooling demand often coincides with cool outdoor temperatures.

Tempering removes the contribution of mechanical ventilation to the temperature sensitivity of heating and cooling demand, which results in the form of cooling energy signature shown in Fig. 2. This form of cooling energy signature has two segments, a base temperature corresponding to the fabric heat gains only and a change of gradient at the upper supply temperature limit for tempering[1]. The air system still provides a degree of cooling—the supply temperature is below the room temperature, but the majority of the cooling is provided by the water (or refrigerant) subsystem.

2.1.2.3. Pre-cooling. In hot climates where the outdoor air temperature is frequently above the desired indoor temperature, air conditioning systems may use heat exchangers to pre-cool the incoming outdoor air by transferring heat to the cooler exhaust air. This will reduce the temperature sensitivity of the cooling consumption at times when the outdoor temperature exceeds the indoor temperature.

2.1.2.4. Free cooling. All-air systems meet peak cooling demands entirely through the supply of cooled air and therefore have relatively large air supply volumes. When the outdoor air temperature is below the indoor temperature and there is a cooling demand, the proportion of outdoor air in the air supply can be increased above that needed purely for ventilation, providing "free cooling" without

[1] There is a corresponding change of gradient in the heating energy signature at the same outdoor temperature, reflecting the additional heating that is required.