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A novel method of determining events in combination gas boilers: Assessing the feasibility of a passive acoustic sensor

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ABSTRACT

To assess the impact of interventions designed to reduce residential space heating demand, investigators must be armed with field-trial applicable techniques that accurately measure space heating energy use. This study assesses the feasibility of using a passive acoustic sensor to detect gas consumption events in domestic combination gas-fired boilers (C-GFBs). The investigation has shown, for the C-GFB investigated, the following events are discernible using a passive acoustic sensor: demand type (hot water or central heating); boiler ignition time; and pre-mix fan motor speed. A detection algorithm was developed to automatically identify demand type and burner ignition time with accuracies of 100% and 97% respectfully. Demand type was determined by training a naive Bayes classifier on 20 features of the acoustic profile at the start of a demand event. Burner ignition was determined by detecting low frequency (5–10 Hz) pressure pulsations produced during ignition. The acoustic signatures of the pre-mix fan and circulation-pump were identified manually. Additional work is required to detect burner duration, deal with detection in the presence of increased noise and expand the range of boilers investigated. There are considerable implications resulting from the widespread use of such techniques on improving understanding of space heating demand.

1. Introduction

1.1. Motivation

Approximately 72% of energy consumption in the domestic environment is done so in gas-boilers for the purposes of domestic central heating (DCH) and domestic hot water (DHW) production [4]. Being such a large contributor to domestic energy consumption, gas-boilers have received significant attention from policy makers and researchers alike. In accordance to the UK Government's CO_2 target of an 80% reduction in emissions by 2050 [28], amongst other actions, policy makers have modified building regulations [11] so that boilers installed after 2006 are required to have a SEDBUK [2] efficiency of 88% or above. In addition to policy changes, many researchers look to evaluate environmental or behavioural interventions designed to reduce DCH and/or DHW consumption. To evaluate such interventions it is necessary to accurately monitor changes in disaggregated operational energy consumption, often in field trials.

Measuring energy consumed for DCH in field trials has however proven a challenge, as Hong et al. [12] note: due to the "… high cost associated with sophisticated fuel-use monitoring equipment required for different types of heating system and the complexity of its installation". Estimates of DCH energy use have been made in a number of studies by subtracting the summer fuel load from the winter fuel load [12,36]. These methods however require more than one years' worth of data and assume no variation occurs for non-space heating energy use between seasons. Other studies, such as Martin and Watson [22] and Love [23], used temperature sensors on flow pipes or radiators and relate temperature increases to boiler firing. These methods however miss short burner cycles and burner modulation. If methods were available that could accurately detect burner duration and modulation, space heating energy consumption estimates would be more accurate.

In addition to the above, it is well established that unnecessary cycling of boilers is undesirable [24]. Frequent on/off cycles, for example, cause boilers to operate at efficiencies "well below (their)

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full-load bench value" [38]). This issue has been observed in practice, for example Ren et al. [32]) note "Space heating systems cycled more frequently than anticipated due to a tight range of room thermostat settings and potentially oversized heating capacities." Likewise a survey of 35 non-residential buildings revealed that "all of the installed heating capacity was oversized by a minimum of 30% …" [21]). Furthermore unnecessary cycling causes additional wear and tear on components. These problems can be due to oversizing [10], incorrect return flow temperature sensor settings, inadequate boiler modulation ranges etc. Data on cycling rates and boiler modulation could thus help identify potential issues causing efficiency losses.

Thus to accurately evaluate interventions designed to reduce demand, new field-trial applicable methods are required that can accurately measure operational burner duration for space heating purposes. Additionally such methods could be used to provide data on operational boiler cycling behaviour and help identify potential efficiency losses due to setup, design and/or sizing issues.

1.2. Aim

The aim of this study is to assess the feasibility of a single-point acoustic sensor and associated detection device that can be retrofitted to Combination Gas Fired Boilers (C-GFB) to provide data on energy consumption, demand type, boiler operation and boiler failure modes. Primary events for detection include demand type and the burner duration. Secondary events include the activity of the pre-mix fan and circulation-pump. Note, the circulation-pump circulates heating water around the closed heating system circuit (boiler, radiators etc.) and the pre-mix fan draws both natural gas and air into the burner chamber and helps to expel the exhaust gases. C-GFBs were selected for this study because, as of 2011, 60% of DCH and DHW systems in the UK were of this type. Additionally the number of C-GFBs has risen steadily since 1990, with no indication of it decreasing in popularity [4].

For this investigation, event detection will use the acoustic signal produced by the physical process of the event itself. This is to avoid making the assumption that the expected process flow of the system is being followed. For example, changes in the pre-mix fan motor speed are directly related to the period of firing, however using the pre-mix fan motor speed as a basis for detecting firing would assume the boiler is behaving as expected. Thus, the investigation bases burner identification on the acoustic signal produced by the burner and not the acoustic signal produced by any other component of the system. By doing so, events occurring outside of the expected process flow of the boiler can potentially be detected.

Alternative methods of event detection exist. One method is to monitor the boiler's Central Processing Unit (CPU). Junkers (the German brand of Bosch), for example, have developed a smartphone application which is linked via a wireless network with the CPU of some Junkers boilers [18]; however the application doesn't give detailed information on boiler events such as ignition time (only failure codes are reported back to the user). In general, accessing a boiler's CPU requires manufacturers' consent and substantial proprietary software, and if performed by research fieldwork teams, could invalidate boiler warranties. The advantage of using a non-invasive retrofitted method, such as an acoustic sensor, is that warranties are not invalidated and theoretically all boilers are accessible irrespective of age, software or hardware. Another option would be to use multiple sensors: The sensors however would need to be situated in various locations depending on the boiler. This increases both cost, complexity and the probability of sensor failure. The advantage of a single acoustic sensor is that most events of interest could, in principle, still be detected, and that the exact positioning of such an acoustic sensor would be of less importance and could sit externally to the boiler.

2. Related work

This study is focused on identifying techniques to determine events of interest from the acoustic signals produced by domestic C-GFBs. No studies can be found in the literature of this nature, however related studies exist that apply signal analysis techniques to determine resource usage in the domestic environment and they include: the determination of electrical component usage from the electrical mains signals [9,29]; the localisation of water valve usage from water pipe pressure fluctuations [7]; and derivation of gas component usage from the acoustics of gas relief valves [3]. The general technique applied in all these studies involved the use of supervised-machine-learning (SML) algorithms. SML algorithms comprise of a set of procedures which automatically create models to determine the events of interest when the events are unknown, from a set of training data when the events are known; Refs. [20,41] provide overviews. The training data used in these studies comprise of a specifically selected set of features within the signal called feature vectors.

In the determination of electrical devices (switched-mode power supply only) used in the home, Gupta et al. [9] analysed the electromagnetic interference signal created in the domestic mains voltage supply during device operation. They selected the amplitude, mean and standard deviation of any voltage peak in the frequency domain as feature vectors. As the number of dimensions were low the k-Nearest Neighbour (kNN) classification algorithm was applied. The cross validation accuracy (Refer to Ref. [19]; p.2–3) of the classifier was 94%. After calibration this detection method was then tested across seven individual homes and found to work with accuracy greater than 90%. Patel et al. [29] develop a similar classification algorithm for detection of resistive and inductive electrical devices. The research of Patel et al. [29] and Gupta et al. [9] is complimentary; together they cover the detection of all electrical component types.

Sensing and classification algorithms have also been applied to the analysis of domestic water consumption. Froehlich et al. [7] built on the work done by Fogarty et al. [6] in the development of a sensor to detect faucet flow-rate and location. Froehlich et al. [7] used a customized pressure sensor attached to a fixture within the household to detect shockwaves created when faucets open or close. The signature of the shockwaves were found to be unique depending on the valve type and location. Thus Froehlich et al. [7] were able to create classification algorithms to determine the fixture, its location and estimate the flow-rate. Two layers of hierarchical classifier were applied to determine if the valve had been opened or closed and its location. Once a valve event was determined features were extracted to identify the fixture location, these were: (1) the matched filter; (2) the matched derivative; (3) the real part of the Mel Frequency Cepstral Coefficients (MFCCs); and (4) the mean squared error: mathematical definitions of which can be found in Ref. [37]. This method resulted in an average cross-validation accuracy of 98% when identifying fixtures across multiple homes (10 homes were tested). Estimates of the flow rates on three houses showed average errors below 8% (comparable to utility supplied water meters). Note that MFCCs are widely used as features for speech recognition technologies [25] as they correspond more closely with the human auditory perception [14].

In the application to gas usage, Cohn et al. [3] present a method for single-point acoustic sensing of individual domestic gas appliance usage. They analysed acoustic signals emanating from a Government regulated gas relief valve; a valve that is installed in most US homes. Signals from the gas relief valve were isolated from unwanted background noise using a high-pass filter. A linear