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Determining appliance energy usage with a high-resolution metering system for residential natural gas meters

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HIGHLIGHTS

- A module has been developed to detect usage signatures of gas-consuming residential appliances.
- The module contains a high-resolution mechanical encoder to resolve small volumes of gas.
- A module that includes the encoder can be retrofitted to standard gas meters in the US.
- The non-linear motion of the gas meter has been analyzed and accounted for.
- Flow rates from 7 ft^3/h to 250 ft^3/h can be measured, with a resolution of 0.01 ft^3.

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ABSTRACT

This paper presents a high-resolution automated meter reading system for residential gas meters, which can be used to record gas consumption for each appliance. The mechanical operation of an industry-standard residential gas meter is characterized, and the internal metering mechanism analyzed to develop a system to non-intrusively monitor gas consumption of individual appliances by resolving small amounts of gas usage at the meter. The system can be retrofitted to an existing gas meter with a module that includes a high-resolution encoder to collect gas flow data, and a microprocessor to analyze and classify appliance load profiles. This approach provides a number of attractive features including low cost, easy installation and integration with existing meter reading technologies. This system enables gas utilities to provide real-time feedback to customers on gas usage by appliance.

1. Introduction

Natural gas is the fuel of choice for more than 40% of households in the US, with nearly 140 billion m^3 (5 trillion ft^3) consumed annually [1]. Residential customers receive gas via a dedicated piping infrastructure provided by a local utility. The supply lines are connected to mechanical gas meters that utilize an internal positive-displacement flow mechanism and a mechanical index to record the total volume of gas consumed. The vast majority of gas meters are read manually at monthly intervals to determine gas usage for customer billing.

The smart grid is a rapidly developing concept intended to improve the delivery of electricity, gas and water utilities. Smart meters installed at the utility endpoints to monitor usage are an important component of the smart grid. The current state of the art in smart meters includes wireless meter reading, two-way communication and security features [2,3]. More advanced features for smart meters are still being developed. For a smart-grid-based natural gas meter, this work presents a technique to resolve the metered gas volume in much smaller increments than currently possible. This information can be used to determine the operating history of individual appliances by analyzing measurements made at the entry point of a home, enabling more efficient management and utilization of natural gas. This concept is not new, with similar concepts collectively referred to as *Non-Intrusive Appliance Load Monitoring* (NIALM) in the literature. The idea was first proposed for electricity by Hart [4–6], but his algorithms were only viable for electrical appliances with large loads and constant power consumption profiles. NIALM algorithms were later improved to handle more electrical appliances and resolve more specific loads for electrical systems by Laughman et al. [7], Farinaccio and Zmeureanu [8] and Leeb et al. [9]. Significant advances have since been made in monitoring electrical loads non-intrusively [10,11].

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NIALM techniques have also been applied to sub-meter water and gas utilities. Fogarty et al. [12], Kim et al. [13] and Larson et al. [14] have applied NIALM techniques to disaggregate water usage in residential homes. The first practical application of NIALM for natural gas was presented by Yamagami and Nakamura [15]. They installed data loggers on meters in Japanese households and applied Hart's steady-state method to sub-meter gas usage. Another approach utilizing the acoustic response of gas meter pressure regulators was presented by Cohn et al. [16].

Developing NIALM techniques for gas meters has presented unique challenges [15]. Yamagami and Nakamura concluded that their system could not consistently identify variable rate gas appliances and had an overall error rate of 5% [15]. Their algorithms were also implemented on specialized high-resolution residential gas meters used in Japan. Cohn et al. reported that they were not able to accurately measure low flow rates, and experienced issues with background noise and difficulties distinguishing between concurrent appliance usage [16].

It is costly and labor-intensive to replace an existing, mechanically plumbed gas meter, e.g., with a modern ultrasonic gas flow meter. An interruption of gas service and a post-install inspection of the gas supply system are also required. A less costly approach is to retrofit existing meters with a module (Fig. 1) that can be installed in a few minutes time to an existing meter without having to disconnect or interrupt service. Several different designs for a retrofit module are currently in use [17–19]. Most provide wireless automated meter reading (AMR) capabilities to record daily or hourly usage information. However, none of these modules provide a high-resolution metering capability and none have provisions for NIALM.

This article presents a high-resolution metering system that can resolve small (<0.3 L or 0.01 ft^3) volumes of natural gas using an existing installed gas meter. The high-resolution usage data can then be used to identify which appliances in the home are consuming gas, from which an aggregate summary of total gas usage and usage times can be compiled. This smart-grid-inspired concept, called *Meter Resource Tracking* (MRT), can be applied retroactively using a module that can be installed on existing gas meters, and can also be combined with existing wireless AMR solutions.

Gas meters equipped with MRT can enhance the smart grid in several ways. Gas utilities can benefit from appliance-level gas usage information in a similar manner to electrical utilities. They can use the data to make more accurate estimates of which gas appliances are responsible for most of the energy consumption inside a home, perform load research, monitor demand-side management programs, properly evaluate their conservation programs and address billing complaints. In addition, because meters equipped with MRT have a higher resolution, very small flow rates can be detected more easily. Such flow rates may represent irregular appliance operation (sticking valves/restricted flow), theft, or leaks. For customers, MRT can provide real time appliance usage data through an in-house display or on the web. This information can be used by customers to minimize consumption and reduce cost [20–22]. MRT data can also be used to compare efficiency and costs when considering upgrading to energy-efficient appliances. This can provide customers realistic estimates on the payback time of investing on new higher-efficiency appliances. Inconsistent usage trends can be identified by comparing the latest usage profiles against historical records and notify the customer, e.g., if an appliance usage rate changes drastically, and recommend a cleaning/inspection. Leaks or sudden increases in gas consumption can similarly be detected.

1.1. Residential natural gas usage characteristics

Gas utility usage differs from electricity in several ways. The main uses of natural gas in residential homes include heating, cooking and hot water. Typically there are only a few gas appliances inside a home to meet these needs, e.g., furnace, hot water heater, dryer and stove/oven. This is different from electrical usage, in which 30–60 electrical appliances can exist in a household.

A second distinguishing feature of most gas consuming appliances is that they have a constant consumption rate when there is a call for gas. Such appliances do not provide a mechanism to control the amount of gas flow, i.e., they are either fully on or off. Exceptions include a stove/cooktop that can be regulated with a variable gas flow adjustment. In contrast, many electrical appliances have variable electricity consumption rates, e.g., light dimmers, variable speed motors, and stereo systems. A binary consumption load profile is easier to detect than one that is continuously variable.

The ability to decompose the aggregate usage profile to individual appliance loads is dependent on the number of appliance on–off states. For n appliances, there are $2^n - 1$ ways in which they may be combined to be on. A small number of appliances results in a feasible number of on–off combinations, e.g., if there are 4 gas consuming appliances inside a home, there are only 15 unique ways they can be on or off. In contrast, if there are 30 electrical appliances, there will be over a billion on–off states, making it significantly more difficult to decompose the total load profile.

Finally, there are unique features in the usage signature of individual gas appliances. These include usage frequency, cycling frequency and time of usage in a 24 h period. Furnaces usually consume gas in long, constant intervals while dryers are used infrequently with short on–off cycles. Other appliances like cooktop/oven or water heaters are used at specific times of day.

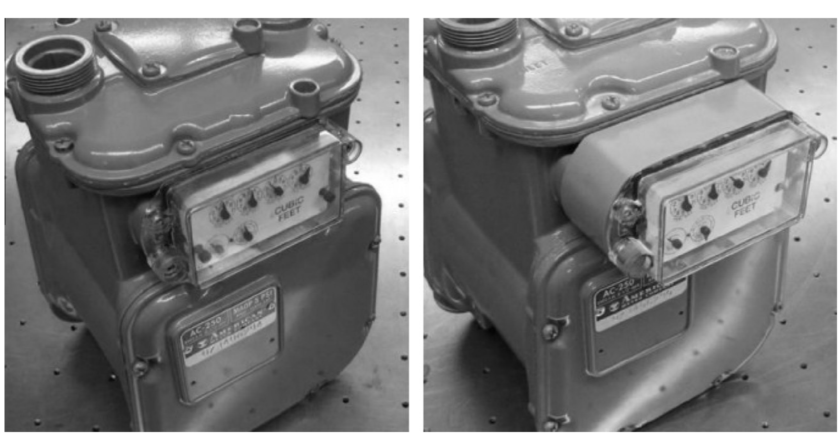

Fig. 1. Retrofit assembly & attachment to meter.