Applied Energy 155 (2015) 242–252

Contents lists available at ScienceDirect

Applied Energy

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

Development and operation of a self-refueling compressed natural gas vehicle

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HIGHLIGHTS

- A mode switching natural gas SI engine was developed and then installed in a vehicle.
- The engine can compress NG and combust in the same cylinder at different times.
- The vehicle was driven on public streets using its own CNG for 161 km.
- The system can increase the adoption rate of NG fuel in transportation.

ARTICLE INFO

Article history:
Received 15 January 2015
Received in revised form 14 May 2015
Accepted 25 May 2015

Keywords:
Natural gas
Transportation
CNG
NGV
Compressor
Home refueling

ABSTRACT

A dual-mode engine has been developed where in one mode all engine cylinders fire normally, providing locomotion for the vehicle. In the other mode, one cylinder of the engine is used to compress low pressure residential natural gas (NG), in multiple stages, to a standard U.S. compressed natural gas (CNG) vehicle storage tank pressure of 248 bar [3600 psig]. This allows a natural gas vehicle (NGV) to be refueled anywhere there is access to the natural gas distribution network. Experimental studies were conducted on this prototype engine and are reported here. Knowledge gained from applying numerical models combined with empirical results led to the realization of a self-refueling natural gas vehicle. On the test stand, air (a surrogate for NG) was compressed by the engine to over 138 bar [2000 psig] filling an 11.8 GGE [140 L] tank in 150 min. On the vehicle platform, the integral compressor had an approximate refueling efficiency of 70%, with an electrical-equivalent parasitic load of 12.6%. Idling of non-compression cylinders and the distance between the compressor and the three-way valves used to control the compression staging were noteworthy sources of inefficiency within the system. At the conclusion of the project the vehicle powered by the dual mode engine was driven over 161 km [100 miles] using self-compressed natural gas which originated from the local utility.

1. Introduction

Compared to traditional fuels like gasoline and diesel, combustion of natural gas (NG) releases much less CO_2 into the atmosphere, a potent greenhouse gas (GHG) [1]. In fact, NG emits less CO_2 per unit of energy than any fossil fuel [2]. It has been shown that the use of CNG in a retrofitted gasoline engine can result in lower emissions of carbon-monoxide, carbon-dioxide, and unburned hydrocarbons [3]. The adoption of NG as a transportation fuel can act as a transition step towards a low carbon future where transportation relies on renewable sources of energy [4,5]. For further discussion of the impact of NG on GHG emissions, please consult Moniz et al., Peterson et al., or Curran et al. [2,6,7]. Despite these benefits, only 0.03% of the 26.13 trillion cubic feet (Tcf) of NG consumed in the U.S. during 2013 was used for vehicle fuel [8].

Over 60 million homes and businesses in the United States (U.S.) are connected to the NG supply network [9]. The proliferation of horizontal drilling and shale gas made accessible by hydraulic fracturing has unlocked huge supplies of NG in the U.S.. According to the U.S. Energy Information Administration, shale gas drilling accounted for 9.7 Tcf of NG production in the U.S. during 2012 and is forecasted to grow to 19.8 Tcf by 2040 [10]. This increase in natural gas reserves has led to the decoupling of domestic NG and global petroleum prices, with the price of NG falling substantially [11]. It was stated by Peterson et al. that natural gas vehicle (NGV) adoption is influenced by the required payback period and infrastructure growth, but primarily driven by low NG prices and correspondingly high oil prices [6]. NG must be

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http://dx.doi.org/10.1016/j.apenergy.2015.05.116

Nomenclature

γ	ratio of specific heats, –	bar	pressure, $10^5\ \frac{N}{m^2}$
η	efficiency, %	kPa	pressure, $10^3\ \frac{N}{m^2}$
Ψ	parasitic load, %		

compressed in order to achieve an acceptable vehicle driving range. Typically the gas is stored inside a compressed natural gas (CNG) tank pressurized to 248 bar [3600 psig], which has about a quarter the energy density of gasoline [7].

In many locations, the retail price difference between gasoline or diesel and CNG can be over $2.00 per a gallon of gasoline equivalent (GGE) on an energy basis. This price difference is expected to continue for several decades, owing primarily to the abundant domestic supply of NG [12]. This presents an opportunity for individuals and fleet owners to save a large amount of money on fuel cost for vehicles, with greater savings occurring the more miles driven. NG usage for transportation provides benefits beyond the GGE cost savings over conventional fuels. An increase in U.S. NG-fueled vehicles will reduce regulated air emissions, increase revenues spent on domestic NG exploration and production, and decrease dependence on imported petroleum [13,14].

As of October 2014, there are 770 public CNG refueling stations in the U.S., compared to over 100,000 gasoline stations (as of 4th quarter 2012) [15,16]. There are very few passenger cars available which use NG as a fuel, partly because of the lack of convenient refueling stations. Often referred to as fast-fill stations, refueling times at these locations are similar to conventional gasoline stations. One reason for the current absence of CNG refueling stations is capital cost. A CNG station costs around $1.7M to construct compared to around $150,000 for the average gasoline station (assuming three underground storage tanks) [17,18]. Interestingly, the lack of refueling infrastructure can also be attributed to minimal consumer demand due to the limited number, and higher price, of CNG vehicles available from automakers [6]. In the work described here, the combustion and compression functions are combined into a single cylinder, creating an on demand integral compressor for vehicular applications. This allows a NGV to be refueled anywhere there is access to NG, even if the NG is at very low pressure, thereby removing the fueling infrastructure barrier inhibiting widespread adoption of CNG for U.S. transportation.

This internal combustion engine (ICE) operates in two distinct modes. In one mode, all engine cylinders fire normally providing locomotion for the NGV. In the other mode, one cylinder of the engine is used to compress low-pressure residential NG (0.017 bar [0.25 psig]), in multiple stages, to a standard U.S. CNG vehicle storage tank pressure of 248 bar [3600 psig]. When in this mode, the remaining engine cylinders idle to provide the necessary compression energy. Experiments were conducted to evaluate the performance of the compressor first using air as the working fluid and subsequently NG. This paper contributes to existing literature by: (1) establishing a new, alternative method to produce CNG fuel for a NGV to further facilitate the adoption of NG in transportation, (2) presenting a novel dual-purpose engine cylinder for use with NG, (3) experimentally characterizing a proof-of-concept self-refueling vehicle, and (4) comparing the new concept to existing CNG fueling technology.

The ensuing parts of this paper present and discuss the development and operation of the self-refueling NGV. In the next section entitled Background, a brief summary of past integral natural gas compressors and at-home natural gas refueling compressors is given. A more detailed description of the bimodal engine is presented in Section 3 along with descriptions of the various iterations of laboratory experimental setups. Section 4 presents the logic created to automate the refueling process. Next, Section 5 presents pertinent results from experimental testing and discusses the implications of these results. Finally, Section 6 presents observations and conclusions gleaned from the experimental work.

2. Background

It was shown by Robinson and Beaty that reciprocating compressors are effective for compressing gases to high pressure ratios [19]. Furthermore, integrating a compressor into an internal combustion engine is not novel. For example, in the oil and gas industry wellhead boosters are used to pressurize NG at the drilling site for low pressure wells. In the 1970s GrimmerSchmidt began selling their MonoBlock air compressors and NG well boosters. This compressor used four cylinders of a V-8 engine for compression of air or NG while the other four cylinders supplied the mechanical work [20]. More recently (circa 2000), and led by economics, wellhead gas boosters such as the GasJack became increasingly popular to increase production from shallow, near-depleted well sites. The addition of a compression booster to a well site is capable of doubling or tripling daily production on gas wells producing less than 500 Mcf per day [21]. The GasJack booster uses a modified 460 Ford V-8 engine where one bank of cylinders, unchanged from the stock engine, burns NG from the well (assuming it is suitable for burning). The second bank of cylinders is outfitted to pump natural gas.

Functional at-home NG refueling has a precedent, namely a line of small scale (1–5 kW [1.3–6.7 HP]) NG compressors that have been available to U.S. consumers for some time. A prime example of a home refueling NG compressor is the Fuelmaker Phill [22]. The Phill is a home refueling compressor that can be installed indoors or outdoors to refuel a CNG vehicle using residential pressure NG. It is a multi-stage reciprocating compressor, with four compression cylinders of successively smaller volumes coupled to a common crankshaft. The total cost including installation is typically over $6000 [23]. The following will briefly outline the performance of this compressor such that a comparison can be drawn with the new compressor presented in this paper.

The unit will compress gas to 248 bar [3600 psig] at a flow rate of 0.5 Gasoline Gallon Equivalent (GGE) per hour using 0.85 kW h of energy on average, according to the manufacturer [22]. At this refueling rate, in one hour, the gas compressed would represent 60,138 kJ [57,000 BTU] of chemical energy. Assuming the electricity used came from a thermal power plant with a heat rate of 9496 kJ/kW h [9000 BTU/kW h] (i.e., 37.9% BTE) and transmission and distribution losses are 8%, then the compression penalty (parasitic load) associated with the Phill compressor is approximately 14.3%. This device is considered state-of-the-art for residential CNG vehicle refueling. The primary disadvantage of the device and home refueling in general is the fill rate. If a vehicle had an 11.8 GGE CNG tank, it would take nearly 24 h to completely fill up. With this disadvantage in mind, the current project aimed to use the engine itself for compression to improve fueling times.

3. Methods

In the following, after the bimodal engine concept is more thoroughly explained, the laboratory experimental setup is presented