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Design considerations for an engine-integral reciprocating natural gas compressor

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HIGHLIGHTS

- An engine-integral natural gas compressor was developed under contract to ARPA-E.
- System is novel in that an engine powers its 6th cylinder as a multi-stage compressor.
- A structural and functional description of the system is presented.
- Dynamic and thermal characteristics of the system dictate the design.

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ABSTRACT

Conventionally, compressed natural gas (CNG) vehicles are refueled using a high-cost, centralized, and sparse network of CNG fueling stations that has primarily been developed for the use of fleet customers. An engine-integral reciprocating natural gas (NG) compressor has the capability to disrupt the incumbent CNG market by enabling the use of NG for personal transportation, fueled at home, from the preexisting low-pressure NG infrastructure, at low parts count, using conventional components, and therefore at low incremental costs. The principal objective of this paper is therefore to describe and analyze the dynamic and thermal design considerations for an automotive engine-integral reciprocating NG compressor. The purpose of this compressor is to pressurize storage tanks in NG vehicles from a low-pressure NG source by using one of the engine cylinders as a multi-stage reciprocating compressor. The engine-integral compressor is developed by making changes to a 5.9 l displacement diesel-cycle automotive engine. In this novel design and implementation, a small tank and its requisite valving are added to the engine as an intermediate gas storage system to enable a single compressor cylinder to perform two-stage compression. The resulting maximum pressure in the storage tank is 250 MPa, equivalent to the storage and delivery pressure of conventional CNG delivery systems. Dynamic simulation results show that the high cylinder pressures required for the compression process create reaction torques on the crankshaft, but do not generate abnormal rotational speed oscillations. Thermal simulation results show that the temperature of the storage tank and engine increases over the safety temperature of the natural gas storage system unless an active thermal management system is developed to cool the NG before it is admitted to the storage tanks.

1. Introduction

Transportation is a major contributor to the productivity of the US economy, but the air pollution costs, and fuel import costs of a petroleum-fueled transportation system are high. Transportation produces 79% of the "criteria" air pollutants, 50% of total nitrogen oxide emissions, 26% of greenhouse gas (GHG) emissions, and 42% of total volatile organic compound emissions in the U.S [1]. Although regional air quality and the specific GHG emissions (kg/km) of transportation have been improving with advancements in transportation technologies, many regions of the US do not meet federal requirements for air quality [2], and total GHG emissions continue to increase [2]. Transportation fueled by natural gas (NG) engines has been demonstrated to produce fewer CO_2, CO, and HC emissions than gasoline vehicles [3,4], and it is a

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near-term feasible technology for improving the sustainability of the transportation sector [5].

Compressed natural gas powered vehicles (CNGVs) have not become mass-market vehicles in the US for a variety of reasons [6–8]. Consumer and fleet adoption of natural gas powered vehicles are hampered by sparse fueling infrastructure, limited driving range, and the incremental cost of NG vehicles relative to conventional petroleum vehicles. NG fueling infrastructure primarily consists of a sparse network of non-public fueling stations. There are approximately 1300 NG fueling stations in the US [9], as compared to >150,000 gasoline stations. The scarcity of NG fueling infrastructure is exacerbated by the limited driving range available from conventional CNGVs. For example, the driving range of a Chevrolet Cavalier dual-fuel compressed natural gas (CNG) vehicle is 110 miles, approximately 1/3 of the driving range of a conventional vehicle. Finally, NG-powered vehicles have a several thousand dollar[2] higher purchase price than conventional petroleum powered vehicles. CNGVs are therefore subject to the conundrum in which inadequate infrastructure limits the market for the CNGVs, and the limited market for the vehicles discourages investment in a costly CNGV fueling infrastructure.

Many researchers believe that the solution to the NG infrastructure and cost conundrum is the development of localized (as opposed to centralized) business or home NG compressor and refueling systems [10–12]. A localized refueling system would compress the low pressure NG that is delivered to many businesses and homes through the preexisting, low-pressure NG infrastructure and would transfer the compressed NG to the vehicle. This concept has several advantages over the more conventional centralized CNG infrastructure solutions [13]. First, the allocation of fueling infrastructure costs to a single vehicle means that the cost and availability of the fueling infrastructure is independent of the state of CNG vehicle market penetration. Second, by placing fueling infrastructure at the locations where the vehicle regularly parks, refueling can be performed daily or more often without inconvenience to the driver. The primary challenge that must be overcome to improve the feasibility of localized refueling infrastructure is its cost. There exist a variety of localized (home) NG compression systems that will fuel a CNG vehicle by locally compressing the NG available from low-pressure residential-type infrastructure. These systems have a high incremental cost because they are not subject to mass-production, they have tight tolerances and parts count, and they require high-power, high-torque power supplies.[3] Engine-integral air compressors are commercial products[4], although no similar systems have been developed to produce compressed NG [14]. The most comparable systems design effort that the authors are aware of is in the field of integral free piston engine/compressor design [15].

This article proposes the development of an engine-integral, low-parts count, reconfigurable NG compressor as a disruptive technology to address the cost barrier to localized NG compression and fueling. During normal driving, all 6 cylinders of the engine operate under a conventional Otto internal combustion mode. During a refueling event, this concept allows the engine controller to reconfigure one of the engines' combustion cylinders (cylinder 1) to function as a reciprocating multi-stage compressor that directly refuels the vehicle's CNG tank using the low-pressure residential NG infrastructure. This functional change is achieved through a change in valve control algorithms. Such a system allows for the advantages of home CNG refueling while minimizing the incremental cost of materials, components and systems. To characterize this disruptive technology, this article describes the structural and functional concept, and provides a set of thermodynamic and mechanics models and results to characterize the design requirements of the system. Finally, we propose our understanding of the barriers that must be overcome to enable the technical and commercial viability of the technology.

2. Structural description

This section describes the vehicle components and mechanical systems that make up the engine-integral compressor system. The primary components of the engine-integral compressor system are the CNG tanks, the CNG internal combustion engine (ICE), the intermediate pressures storage tanks (IPST), and the system of control valves, as shown in Fig. 1.

CNGVs store natural gas in high-pressure on-board tanks that have rated pressures of 25 MPa (in the US) [16]. Conventionally, these tanks are filled from a high-pressure connection to a high-pressure CNG refueling system. In this concept, we seek to fill the on-board CNG tank by compressing NG from line pressure (~1.02 bar absolute) to tank pressure using an engine-integral compressor. Fueling the on-board tank using low-pressure NG minimizes the need for a high-pressure CNG infrastructure.

CNG-powered engines are similar in structure and control to conventional ICEs. Modified NG injectors and emissions control equipment are often used to convert conventional ICEs to NG-powered ICEs. In this concept, by using the internal components of the ICE as a reciprocating compressor, we can reduce the parts count and therefore manufacturing costs of the integral compressor and engine systems. In this concept, a reciprocating compression cylinder is powered mechanically from the engine crankshaft as the other 5 cylinders perform conventional ICE operations. A modified diesel-cycle engine is chosen for this concept description to allow the mechanical components of the engine to tolerate repeated in-cylinder pressures of up to 25 MPa.[5]

Conventional diesel engines have compression ratios (CR) of between 14 and 22, primarily limited by clearance volume requirements, and diminishing returns on engine efficiency with increasing CR [18]. Because of this CR limitation, in this concept the pressurization of the NG from line pressure to tank pressure must be performed in multiple stages. In this concept we use "intermediate pressure storage tanks" (IPST) to store intermediate pressure NG between the stages of compression to allow for multi-stage compression of the NG to storage pressure using a single compression piston. The IPST are envisioned as rigid, metallic cylinders that are connected to the cylinder with a system of control valves. Under each stage of compression, the cylinder can achieve a compression ratio of between 14 and 22, which implies that between 2 and 3 stages of compression (and therefore between 1 and 2 IPST) are required to generate a tank pressure of 250 bar from the near-ambient supply pressure. In this concept, a Cummins 5.9L Diesel engine is chosen for detailed consideration. Its CR of 17 allows for the use of a single IPST.

The conversion from a conventional engine to an engine-integral compressor system requires the development and installation of a custom engine head that incorporates the valving and flow passages illustrated in Fig. 1. The conventional exhaust and intake valves for cylinder 1 are disabled (closed) during compression operations.

[2] The Natural-gas alternative. The pros and cons of buying a CNG Powered car (http://www.consumerreports.org/cro/2012/03/the-natural-gas-alternative/index.htm).

[3] BRC FuelMaker, http://www.brcfuelmaker.it/eng/casa/phill.asp.

[4] Dunn-Right Inc., "Volks-Air Air Compressor," http://www.dunnrightinc.com.

[5] Heavy-duty diesel engines' maximum pressure has been increasing since 1970 and it is predicted to reach 25 MPa in the near future while future incremental improvements in specific power are predicted [17].