Design considerations for an engine-integral reciprocating natural gas compressor

Mohammad Malakoutirad, Thomas H. Bradley, Chris Hagen

Colorado State University, Department of Mechanical Engineering, Campus Delivery 1374, Fort Collins, CO 80523-1374, United States
Oregon State University – Cascades, School of Mechanical, Industrial and Manufacturing Engineering, 2600 NW College Way, Bend, OR 97701, United States

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 CO₂, CO, and HC emissions than gasoline vehicles [3,4], and it is a...
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 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 NG 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 NG 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. Engine-integral air compressors are commercial products, 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 NG 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.

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.

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].
3. Functional description and analysis

Using the components described in the previous section, this section describes the function and operation of the engine-integral reciprocating NG compression system. In this section, we describe the process of in-cylinder NG compression, the process of transfer of intermediate pressure to and from the IPST, and the process of transfer of high pressure NG to the on-board storage tank.

3.1. In-cylinder natural gas compression process

Upon connection of the vehicle to the home NG fueling line, one of the cylinders of the ICE begins to operate as a compressor powered by the other 5 cylinders of the ICE. Low-pressure gas is admitted into this compression cylinder by way of the fuel control valve, a normally-closed, spring return, solenoid valve. As the piston moves upwards in the cylinder, the NG is compressed. The action of the one-way valve shown in Fig. 1 are such that the cylinder will only transfer pressurized NG from the compression cylinder to the IPST when the in-cylinder NG pressure is greater than the pressure in the IPST. As the cylinder moves past its top dead center (TDC) position, the in-cylinder pressure will reduce until it is below the pressure in the IPST, closing the one-way valve between the compression cylinder and the IPST. The compression cylinder then expands the remaining in-cylinder NG until the cylinder reaches ambient pressure, at which point low-pressure gas is admitted into the compression cylinder from the home NG fueling line. The cycle repeats to provide compression of the NG from the fueling line, and to and from the IPST, in turn.

3.2. IPST tank pressurization process

As described in the preceding paragraph, the NG in the compression cylinder increases in pressure as the cylinder approaches TDC, and the 3 position, normally-closed, spring return, solenoid valve between the compression cylinder and IPST allows the movement of NG from the cylinder into the IPST. Details of the process are shown in Fig. 2. For this conceptual design study, the compression of NG is simulated using a polytropic process (Eq. (1)) with a polytropic exponent (k) of 1.3, whereas the ratio of the volume-constant specific heat to the pressure-constant specific heat for NG is 1.4 [19].

\[ \frac{P_i}{P_f} = \left( \frac{1}{CR^k} \right) \]  

As the compression cylinder passes through TDC, the pressure in the compression cylinder begins to decrease and the solenoid valve between the compression cylinder and IPST is closed by its solenoid actuator. The cylinder expands the remaining NG until new NG is admitted to the cylinder at near-atmospheric pressure near BDC. This process repeats itself until the pressure in the IPST reaches its pressure setpoint (which varies from between 0.7 MPa and 2.8 MPa, depending on the storage tank pressure). Each cycle of compression moves incrementally less mass to the IPST, and increases the pressure within the IPST incrementally less until the pressure in the IPST reaches its pressure setpoint. For the example illustrated in Fig. 2, between two and four rotations of the compression cylinder are required for the IPST to reach its pressure setpoint.

As the pressure in the IPST rises over its setpoint, the compression system begins to implement its second stage of compression. As the cylinder nears TDC, the control valve between the IPST and the compression cylinder opens and the high-pressure NG is transferred from the IPST back to the compression cylinder. This step is what causes the drop in IPST pressure in the cycle after the pressure setpoint is reached (as illustrated in Fig. 2). The solenoid control valve between the IPST and the cylinder closes again when the compression cylinder reaches BDC. At this point in the example, the state of the compression cylinder is that it is at intermediate pressure and temperature and is at BDC. The compression cylinder therefore compresses from intermediate pressure as it moves from BDC and generates high pressure NG to fill the vehicle storage tank, as described in detail in the next section.

3.3. Storage tank pressurization process

The vehicle’s NG storage tank is a simple storage vessel connected to the compression cylinder using a one-way solenoid-controlled valve. This valve simply transfers NG to the storage tank whenever the pressure of the compression cylinder is greater than the pressure in the storage tank. The volume of the storage tank is much greater than the volume of the cylinder or IPST, so that the pressure of the storage tank builds slowly with each cycle of the multi-stage compression process toward a 25 MPa rated pressure. This procedure is shown in various levels of detail in Fig. 3. Early in the compression process, the storage tank is at low pressure and each cycle of pressurization increases the tank pressure by approximately 0.05 MPa. The tank continues to receive compressed NG and increase its pressure until it reaches a final pressure of ~25 MPa.

The functional result of this system and process is an engine-integral, low-parts count, NG compressor as a disruptive technology to address the cost barrier to localized NG compression and fueling.

4. Detailed design considerations

In practice, the function of this complicated system will be constrained by the detailed design considerations surrounding a few key tradeoffs among the system’s components and capabilities. In this section of the paper, we detail these key tradeoffs within two problem domains that were identified through peer review, commercialization workshops, and discussion with ARPAe project managers: dynamic torque loads and thermal considerations.
4.1. Dynamic torques and rotational energy requirements

Generating high pressures in the compression cylinder requires that high torques be applied and received by the engine crankshaft. For the example engine considered in this study, the engine torque pulses due to the compression and expansion of NG inside the engine compression cylinder will cause instantaneous torque spikes up to 1100 Nm. The dynamics of applying large torques to the compression cylinder’s piston, connection rod, and crankshaft journals will have important implications for engine noise, vibration and component lifetime.

One means to analyze these considerations is to model the dynamics of the engine-integral compressor with the objective of quantifying the magnitude of any increase in engine speed fluctuations. The selected engine for this design has a stock flywheel with an inertia of 2.1 kg m², and the instantaneous velocity fluctuation at standard engine operation at 1000 rpm is ±10 rpm. If the engine speed fluctuations are significantly increased by the dynamics of the simultaneous compression and Otto combustion cycles, then the behavior will have to be mitigated to meet durability, noise, vibration, and harshness requirements.

As discussed earlier, during refueling operations, 5 of the cylinders of this engine operate under the normal pressure cycle associated with an Otto cycle internal combustion engine. Relative to the other cylinders, the compression cylinder develops a large torque pulse during its second-stage compression and subsequent expansion processes. As all cylinders share a common, conventional crankshaft, this high torque pulse makes the engine operate with higher speed fluctuation during the NG compression cycle.

To determine the magnitude and direction of this speed fluctuation, we can model the rotational dynamics of the example engine as its cylinder 1 undergoes the compression cycle, and its cylinders 2–6 undergo Otto combustion cycles. For this purpose, we use a simple, dynamic model of 6 slider bar linkages as in [20]. This
calculation assumes that the cylinder 1 (the compressor cylinder) and 6 operate out of phase to show the worst case scenario in which combustion torque in cylinder 6 and expansion torque in cylinder 6 both accelerate the crankshaft. As shown in Fig. 4, the peak pressure in cylinder 1 occurs at 540° of crankshaft rotation (TDC), as is expected for a polytropic compression cycle. The peak pressure in cylinder 6 occurs at ~550° of crankshaft rotation, as is expected for a pure combustion cycle with conventional ignition delay.

The 10° misalignment in peak pressure between cylinders 1 and 6 means that for cylinders 1 and 6, the sum of the integrated torque in expansion is larger than the sum of their integrated torque in compression. Fig. 4 shows the detail of the engine's torque and pressure calculation, and Fig. 5 shows the velocity fluctuation in the crankshaft. As shown in Fig. 5, operating the engine in a combined combustion and compression mode generates a positive crankshaft velocity fluctuation of between 950 rpm and 1000 rpm. Although this represents an increase in engine velocity fluctuations relative to the stock engine model, a 100 rpm speed fluctuation is not abnormal for automotive applications [21].

These results demonstrate that although there may be some durability and NVH mitigating systems required to achieve OEM-level requirements, the high inertia and I-6 architecture of the conventional engine mean that the engine will be able to run without stalling or malfunction while performing compression cycles.

4.2. Thermal considerations and requirements

The CNG will increase in temperature as it is compressed, and must therefore be cooled to enable it to be stored in compliance with regulations [22]. In practice, the rapid compression of NG that this engine-integral compression system makes available would require the active cooling of the NG before it can be placed into the NG storage cylinder. To develop an understanding of the thermal requirements of this cooling system we can model the thermodynamics of the NG compression and heat transfer processes. For this study, heat transfer is considered (1) from the NG under compression to the engine components, (2) from the NG in the IPST to the ambient air, and (3) from the NG in the storage cylinder to the ambient air.

To model the thermal behavior of the NG under compression without the engine cooling system, we can consider the compression as a polytropic process. Under the assumptions of a polytropic compression process (shown in Figs. 6 and 8), the CNG temperature in the compression cylinder and storage tank increases from 300 K at near-atmospheric pressure to more than 900 K at 250 MPa, higher than the materials capability of the CNG tanks. As shown in Fig. 10, IPST temperature does not increase significantly in comparison to the compression cylinder and storage tank because its maximum pressure is smaller than that of the storage tank and compression cylinder.

To consider the effect of the stock engine cooling system, we must consider conductive and convective heat transfer to the
engine components. The first thermal system that the compressed NG comes in contact with is the engine itself including cylinder walls, head, and exhaust valves. These components are thermally regulated during normal engine operation by the engine cooling jacket and heat exchanger systems which have a heat exchange capacity of tens of kW of thermal power. For modeling the thermal

![Fig. 6. NG temperature within the compression cylinder under polytropic compression conditions.](image)

![Fig. 7. NG temperature within the compression cylinder including heat transfer to the engine cooling jacket.](image)
behavior of the gas under compression, we must consider that the wall and NG are not at equilibrium. For this exercise, we consider convection between the NG inside the cylinder and the cylinder wall ($h_{avg} = 10 \text{ W m}^{-2} \text{ K}^{-1}$), zero radiative heat transfer (no combustion), and steady state conduction, using the methods detailed in [23]. The temperature results for the compression cylinder including heat transfer to the engine cooling jacket are shown in Fig. 7. Including the engine coolant system model makes the
temperature excursions of the NG smaller, but the heat transfer to the engine is lower than would be characteristic of ICE operation, suggesting that high temperature gas will be transferred to the IPST and storage tank components of the compression system.

Thermal regulation of the IPST and storage tank is achieved by developing a NG-to-air cooling system. These components are more amenable to air cooling than is the compression cylinder because the storage tank has high volume and surface area, and

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**Fig. 10.** NG temperature within the IPST under the polytropic compression conditions.

**Fig. 11.** NG temperature within the IPST under compression conditions including heat transfer in engine cooling jacket and IPST.
the IPST has lower maximum pressure and therefore lower maximum temperature than the compression cylinder. A model has been developed to show the results of the NG-to-air cooling system including high temperature NG transfer to the tanks, conduction through the tanks \( k_{avg} = 60 \text{ W m}^{-1} \text{ K}^{-1} \) and external forced air convection \( T_{avg} = 300 \text{ K}, h_{avg} = 20 \text{ W m}^{-2} \text{ K}^{-1} \). The temperature results for the storage tank including heat transfer from the tank to ambient air are shown in Fig. 9. The temperature of the IPST without and with cylinder and IPST convective cooling is shown in Fig. 11. For both components, the low power NG to air convective cooling system is able to control the NG temperature. The temperature of the IPST including cooling fluctuates from between 350 K and 270 K depending on the state of the compression cycle, and the temperature of the storage tank is controlled to within 10 K of the ambient.

5. Conclusions and future work

This study has analyzed the design considerations required to enable the development and commercialization of an engine-integral reciprocating NG compressor. The structural and functional architecture of the concept show that the engine-integral reciprocating NG compressor can be constructed with minimal additional parts-count and control system development from conventional diesel ICEs. The rotational dynamics, and thermodynamics of the NG compression system have been identified as design considerations of note and this study has addressed these potential barriers to the realization of the concept. The rotational dynamics considerations can be solved by using an IPST to split the compression forces into two stages, a large-scale 1-6 engine where opposing cylinders are undergoing compression and combustion cycles simultaneously, and an application where engine inertia is high enough to overcome any induced rotational dynamics problems. The thermal considerations can be solved by removing only a fraction of the high-pressure and high-temperature NG from each compression cycle, by maintaining the presence of the conventional engine cooling system to perform thermal regulation of the cylinder and piston, and by enabling simple natural convection around the IPST and storage tanks.

Disruptive technologies are those that can reach customers that are not served by the mainstream product. They are generally technologically straightforward, consisting of off-the-shelf components put together in a new product architecture that can realize different benefits that the incumbent technologies [24]. At present, compressed NG (CNG) vehicles are refueled using a high-cost, centralized, and sparse network of CNG fueling stations. As these systems were designed for the use of fleet customers (an incumbent and high profit margin customer), they are often not available for public refueling. At the same time that the cost of NG to fuel CNGVs has gone down in recent years, a consumer demand for low-cost, utilitarian, and environmentally preferable personal transportation has emerged with the production, and sales of electrified and hybridized vehicles. As such, an engine-integral reciprocating 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. By enabling low-cost NG fuel to enter the personal transportation market, the potential for this or similar technology to disrupt the NG fueling energy sector is high.

References