Analysis of Flow of Compressed Natural Gas Through a Fuel Injector

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ANALYSIS OF FLOW OF COMPRESSED NATURAL GAS THROUGH A FUEL INJECTOR

by

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A Thesis Submitted in Partial Fulfillment of the Requirements for a Degree with Honors (Mechanical Engineering)

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The purpose of this thesis is to discuss the determination of the mass flow rate of compressed natural gas through a Delphi Multec CNG Injector. Three methods are used to find the mass flow rates at various pressures. First, SolidWorks Flow Simulation is employed to calculate the mass flow rate with computational fluid dynamics. An analytical solution to the problem is also presented. Finally, experimental results from a previous year’s Capstone team are presented. Fuel flow curves are provided to compare the results from each methodology. The results from the SolidWorks Flow Simulation and analytical calculation agree at the extrema of the fuel rail pressure range tested, while the experimental results do not concur. Additionally, suggestions for future work necessary to tuning the CNG snowmobile to run on compressed natural gas are given.
To John and Brenda

for being there
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CHAPTER 1: INTRODUCTION

1.1: Background

Each year, the Society of Automotive Engineers (SAE) holds a clean snowmobile challenge in Houghton, Michigan. The objective of this competition is to promote innovation in snowmobile engineering. Teams compete to improve the fuel economy, emissions, noise, performance, and handling of an existing snowmobile. Currently, compressed natural gas (CNG) is not an approved fuel for the competition. The University of Maine is developing a snowmobile that runs on CNG with the hope that the Clean Snowmobile Competition Rules Committee will accept CNG as a viable fuel for the challenge. Compressed natural gas was chosen as the fuel for the snowmobile because it produces considerably fewer carbon emissions and has a higher octane rating than gasoline.

1.2: Problem

The snowmobile that students in the mechanical engineering department are converting to run on CNG is a modified 2013 Arctic Cat XF1100 SnoPro. The snowmobile’s four-stroke engine originally ran on unleaded gasoline. Among other changes to the snowmobile, the original fuel injectors were removed and replaced with three Delphi Multec CNG injectors. Currently, the engine control unit (ECU) operates under assumptions that do not reflect the parameters encountered with the combustion of compressed natural gas. The ECU expects that at a certain pressure ratio and pulse width, a certain amount of fuel will pass through the injectors. However, the modifications to the fuel injection system change the amount of fuel that flows through
the injectors at a certain pressure ratio and pulse width. The ECU is no longer able to predict the amount of fuel that the engine receives, and thus, cannot adapt to the operating conditions to produce a certain mass flow rate to maintain a stoichiometric mixture of fuel and air.

1.3: Objectives

The primary objective of this thesis is to analyze the mass flow rate of compressed natural gas through the Delphi Multec CNG injector. To achieve this, a sample injector is cut in half, and the interior geometry is modeled in Autodesk Inventor. The model is then analyzed in SolidWorks Flow Simulation, a computational fluid dynamics package in SolidWorks, to determine the mass flow rate of CNG through the injector at a certain pressure ratio and pulse width. Additionally, a traditional calculation of the mass flow rate through the injector is performed. The results are plotted on fuel curves and compared with each other and with experimental data from a previous Capstone group. In summary, the goals of this project are to

- Determine the interior geometries of the Delphi Multec CNG injector.
- Create an Autodesk Inventor model of the Delphi Multec CNG injector.
- Calculate the mass flow rate of compressed natural gas through the Delphi Multec CNG injector using the model from Autodesk Inventor with SolidWorks Flow Simulation at various fuel rail pressures.
- Plot a fuel curve for the results of the SolidWorks Flow Simulation analysis.
- Perform a traditional calculation of the mass flow rate through the Delphi Multec CNG injector at various fuel rail pressures.
• Plot a fuel curve for the results of the traditional calculation.

• Compare the results of the SolidWorks Flow Simulation analysis, the results of the traditional calculation, and previously collected experimental data.

• Draw conclusions and make recommendations to future Capstone teams about how to properly tune the engine.
CHAPTER 2: INTRODUCTION TO COMPRESSIBLE FLUID DYNAMICS

General fluid dynamics encountered in most undergraduate college courses involves flow that is assumed to be incompressible. This means that as the pressure is increased on the fluid, the density of the fluid does not change much. Most liquids, since any increase in their density is considered negligible as pressure increases, are considered to be incompressible fluids. For many first-pass calculations in undergraduate college courses, gases can be considered to be incompressible as well.

The fuel that the CNG snowmobile uses, compressed natural gas, cannot be assumed incompressible. The pressure in the CNG tank is 3600 lbf/in\(^2\) (absolute) [1], which is very high compared to atmospheric pressure. Inside the tank, the density of the compressed natural gas is much higher than its density at atmospheric conditions. Any calculations performed with CNG cannot use incompressible assumptions.

Another important topic in compressible fluid dynamics is the Mach number. The Mach number is the ratio of the speed of the moving fluid to the speed of sound of that fluid. Written algebraically, the Mach number is defined in Equation 1 below.

\[ M = \frac{V}{a} \]

where

\( M = \text{Mach Number} \)

\( V = \text{Speed of Moving Fluid} \)

\( a = \text{Speed of Sound of Moving Fluid} \)
To help picture the effect of speed on compressibility, let us first consider a ball moving through the air. When the ball moves through the air at low speeds, the air in front of the ball attempts to position itself outside of the path of the ball. In simpler terms, the air tries to move out of the way of the ball. As the speed of the ball increases, however, the air in front of the ball has less time to move out of the way. Since the air cannot move out of the way, it is compressed to make room for the ball. At high enough speeds, the effect of the ball on the compression (density) of the air can no longer be considered negligible. Conventionally, this speed is when the Mach number reaches $M = 0.3$ [2]. In this example, when the ball attains a velocity that is 30% the speed of sound of the air, compressibility effects are no longer negligible.

The same type of compressibility effect can be seen when compressed natural gas tries to flow through an orifice. When the pressure ratio between both sides of the orifice is low, the compressed natural gas is not forced through the orifice with much velocity. At higher pressure ratios, the compressed natural gas tries to move more quickly through the orifice. As the CNG moves faster, however, the density of the compressed natural gas increases. The density changes must be accounted for if one is to accurately calculate the mass flow rate of fuel that can flow through the orifice.

There is also a limit to how fast the compressed natural gas can travel through the orifice. It is known that the Mach number of a fluid traveling through the smallest cross sectional area of a nozzle can never be greater than $M = 1$ [3]. This means that as the Mach number of the CNG moving through the injector orifice approaches $M = 1$, the mass flow through the injector will even out. After a certain point, increasing the
pressure of the CNG at the inlet will have no effect on the amount of fuel that passes through the injector. This effect is known as flow choking.
CHAPTER 3: MATERIALS AND METHODS

3.1: Introduction to Electronic Fuel Injectors

There are several ways to introduce fuel to an engine. One of these ways is to use an electronic fuel injector, simply referred to as a fuel injector in this document. In its most basic form, a fuel injector is a valve through which fuel passes to go from the fuel rail to the intake manifold. The amount of fuel that the engine receives is not actually varied by the fuel injector, but rather, by the engine control unit (ECU). The ECU is a computer on the vehicle that takes in data about the volume of air entering the engine, the engine speed (in rpm), the chemical composition of the exhaust gases, and other variables. The ECU takes this data, analyzes it, and determines the appropriate amount of fuel that must be injected into the system to achieve stoichiometric combustion at different design points determined by the measured variables. The ECU in the CNG snowmobile currently tries to achieve stoichiometric combustion with improper fuel parameters, so it must be reprogrammed for the engine to run on compressed natural gas. To reprogram the ECU to produce a certain mass flow rate of CNG, the mass flow rate of compressed natural gas under varying parameters must be analyzed.
Fuel enters the fuel injector from the fuel rail through the inlet. For reference, please see Figure 1 above [4]. Inside the injector is a coil of copper wire (labeled as an electric coil in Figure 1), a magnet, and a spring. The ECU sends electric impulses to the electric coil through the electrical connector. When the electric coil is charged, it induces a magnetic charge that pulls the magnet up the fuel injector. This, in turn, removes the plunger from the valve orifice so that fuel can flow through the outlet of the injector.

When the ECU discontinues the electric current to the electric coil, a spring pushes the plunger back down so that no fuel can flow through the injector. Typically, the valve of a fuel injector is specially designed to produce a certain flow pattern of fuel leaving the injector. With a conventional fuel, such as gasoline or diesel, the purpose of the fuel injector is to atomize the fuel, or turn it into a fine mist. Atomizing the fuel is important so that it mixes well with the air and burns more completely in combustion. If the valve is improperly designed or damaged in any way, gasoline or diesel will not flow properly.
out of the injector, reducing fuel efficiency of the engine and producing more wear on the engine. Atomizing the fuel and producing a good spray pattern are not essential to the injection of compressed natural gas. Because CNG is a gaseous fuel, it mixes well with the air and combusts evenly.

### 3.2: Preparation of the Delphi Multec Compressed Natural Gas Injector

#### 3.2.1: The Delphi Multec Compressed Natural Gas Injector

The fuel injector chosen by a previous Capstone team is the Delphi Multec Compressed Natural Gas Injector. It is approximately 2.25 inches long and about 0.75 inches wide, not including the electrical connector which juts out of the side of the injector. The fuel injector used, with part number 28371602, is pictured in Figure 2 at right. For more information on the fuel injector, please see Appendix B.

#### 3.2.2: Cutting the Delphi Multec Compressed Natural Gas Injector

A Delphi Multec Compressed Natural Gas Injector was donated to this research project to help determine its geometry so that the fuel flow can be calculated and modeled. The particular fuel injector used had a damaged O-ring around the input. If this injector had been used in the CNG snowmobile, the seal between the fuel rail and the fuel injector would not have been complete and there would have been a fuel leak.
In order to model the interior geometries of the fuel injector, the fuel injector had to be cut in half. Before anything irrevocable was done to the fuel injector, pictures were taken of the injector in profile, the inlet of the injector, and the outlet of the injector. All pictures contained a ruler for scale. Two of these pictures are shown as Figures 4 and 5 below. The sample fuel injector was then placed in a rectangular mold, leveled, then filled with epoxy. Encasing the injector in a prism of epoxy allows for the injector to be cut in a straight line with ease. The fuel injector was left to cure in the epoxy overnight. Figure 3 above shows the injector curing in the epoxy.

Several methods for cutting the fuel injector in half were proposed. A band saw, a table saw, and a milling machine were all considered but were not used because the teeth might damage the delicate interior geometry of the fuel injector. Using a waterjet was another option, but, since it was so small, there was no good way to keep the injector stable so it could be cut in a straight line. A fourth consideration was to use a belt sander and sand one of the faces of the epoxy prism down until the halfway plane of the fuel injector was reached. This method was also not selected because it would take a considerable amount of time to sand away over a quarter of an inch of material, some of which is metal. Ultimately, a wet tile saw was selected to cut the fuel injector in half. There were no teeth to chew up the interior of the injector, the injector could be easily
controlled as it was being cut, and the method was much more direct than using a sander. While cutting the fuel injector with the tile saw took longer than expected, about thirty minutes, the results were very good. The first pass at cutting the injector was slightly shy of the mid-plane of the injector, so the remainder of the material was sanded off with a belt sander. The injector was then polished using finer and finer sand paper. During the cutting and sanding process, a considerable amount of metal shavings and dust gathered in the crevices of the fuel injector. The fuel injector was meticulously cleaned using dental instruments to remove the debris so that the detailed geometry of the injector could be viewed.

3.2.3: Review of the Delphi Multec Compressed Natural Gas Injector

The Delphi Multec Compressed Natural Gas Injector that was cut in half is shown below in Figure 4. The CNG fuel injector shares some basic similarities with the conventional fuel injector shown in Figure 1 in the Introduction to Electronic Fuel Injectors subsection above. Fuel flow, indicated by the blue arrows, enters through the

---

**Figure 4:** Cross-Sectional View of the Delphi Multec Compressed Natural Gas Injector with Labels
inlet, travels through the injector body, passes through an orifice, and exits through the injector outlet. An electric coil of copper wire receives electric impulses from the ECU and induces a magnetic field that slides the plunger away from the orifice. During the sanding process, the spring that pushes the plunger back to a closed position was removed from the injector by the belt sander, so there is no spring shown in Figure 4. Also, though only one passage through the plunger is visible, there are actually four passages. Only one complete passage is visible because the cutting plane only intersected one of the passages completely. The four passages can be seen in Figure 10 in the Autodesk Inventor subsection below. There are four orifices as well, though the cutting plane only intersected one. The four orifices can be seen in Figure 6 in the next subsection.

3.2.4: Determining the Delphi Multec Compressed Natural Gas Injector Orifice Area

Knowing the area of the orifices in the fuel injector through which the compressed natural gas passes is extremely important to determining the mass flow rate of CNG. The orifices are extremely small, so a precise measuring instrument must be used. Since there is at least a quarter of an inch between the injector outlet and the orifices, calipers would not be able to reach the orifices to take measurements. An alternative way of determining the cross-sectional area of the orifices had to be found.
Using AutoCAD, it is possible to calculate the area within a drawn object. A photograph was taken of the fuel injector outlet with a ruler for scale. The image was then inserted into an AutoCAD drawing. A line was drawn over the picture. The line was an inch in length by the scale of the ruler in the picture. This is the green line shown in Figure 5 at right. The picture was scaled down by a factor of 1 divided by the length (in inches) of the green line. This scaled the image so that the distance between the inch markers on the ruler actually measured 1 inch in AutoCAD.

Upon zooming in on the outlet of the fuel injector, the orifices could be clearly seen. The edges of an orifice were carefully traced with lines and arches. The resulting shape was copied and overlain on the other three orifices to check the shape. The remaining three orifices all had the same shape as the one that was traced. Figure 6 at right shows the traces of the orifices in thin red lines. Note that the shape created by the thin red lines accurately traces the shape of the orifice edges.
The MEASUREGEOM tool in AutoCAD was used to determine the area inside the red traces. The area function was selected, and the area was determined to be 0.0036 square inches. This corresponds to the cross-sectional area of the injector outlet orifices. Figure 7 above shows the calculation of the area of all four orifices.

3.3: Autodesk Inventor and SolidWorks Solution

3.3.1: Autodesk Inventor

Autodesk Inventor is a CAD software that specializes in creating 3D representations of objects. It combines the user-friendly interface of AutoCAD with the functionality of SolidWorks. The software was chosen because of its user-friendly interface and the ability to integrate models created in the software into SolidWorks Flow Simulation (the program used for the computational fluid dynamics part of this research paper, detailed in the next subsection).

An image of the cross-sectional view of the Delphi Multec CNG Injector with a ruler for scale was imported into a new Autodesk Inventor drawing. This is the same image as the one shown in Figure 4 above without the descriptive annotations. The image was scaled so that one inch according to the ruler in the image measured one inch in the Autodesk Inventor drawing.
After the image of the cross-section of the fuel injector was scaled to the appropriate size, the outline of the injector shell was traced. This includes the inlet and the injector channel, the orifice plate through which the compressed natural gas passes, and the outlet of the injector. This does not include, however, the plunger, which will be modeled as a separate part. It was not necessary to model the outsides of the injector carefully as they will not influence the flow through the injector. Thus, the outside casing of the injector is drawn as a straight line between the inlet and the outlet. A centerline was drawn through the center of the fuel injector. This will serve as the axis of revolution when the 3D model is created. The appropriate relations are added to the drawing so that the edges of the interior channel remain parallel to the centerline of the model and so that the orifice plate remains perpendicular to the centerline. It is essential that the lines tracing the orifice plate are perpendicular to the centerline so that when the drawing is revolved, the orifice plate created will be flat. The drawing, which is shown in Figure 8 below, is selected and revolved around the centerline. This creates a 3D model of the compressed natural gas injector.

![Image of the cross-section of the fuel injector with a centerline drawn through the center of the fuel injector.](image)

Figure 8: Tracing the Cross-Sectional Area of the Injector Shell in Autodesk Inventor
The injector model is turned so that the orifice plate is visible. The orifice plate is selected as the new drawing plane. An image of the orifices is scaled to the correct size, and the center of the orifice plate in the picture is aligned with the center of the orifice plate in the model. The orifices are traced in a similar manner to the method used in the Determining the Orifice Area subsection. The orifices were then extruded and cut through the orifice plate. The completed model was examined and saved.

The plunger was also modeled in a similar manner to the rest of the injector. The part was traced using a scaled image (Figure 9 at right) and revolved around a centerline. The four holes through which the fuel flows were assumed to have a constant cross-sectional area and to be perpendicular to each other. These holes were extruded and cut through the plunger. An image of this part can be seen as Figure 10 at right.

An Autodesk Inventor assembly was created from the injector shell part and the plunger.
part. The two pieces were mated so that the plunger was concentric to the injector shell. The plunger was also located so that it was in the fully open position so that fuel flow through this arrangement could be modeled. An image of the completed assembly is shown as Figure 11 below.

![Figure 11: The Completed Injector Assembly in Autodesk Inventor](image)

### 3.3.2: SolidWorks Flow Simulation

SolidWorks Flow Simulation is a computational fluid dynamics package that is incorporated in the SolidWorks Student Edition. Several computational fluid dynamics programs were considered, but ultimately, SolidWorks Flow Simulation was selected. The software was chosen for its compatibility with Autodesk Injector, its simulation customizeability, and its faster run time.

The model of the Delphi Multec CNG injector that was created in Autodesk Inventor was loaded into SolidWorks. The model visibility was changed to transparent so that the internal components of the injector could be viewed. The injector model is
shown below in Figure 12. The gray piece is the injector shell (discussed above), and the purple piece is the plunger.

Before a fluid flow analysis can begin, the model must enclose a volume, meaning the inlet and outlet must be capped. To cap the injector, click on the “Create Lids” tool from the upper left of the Flow Simulation ribbon, and select the faces across which the injector should be capped. For this model, the injector was capped across the inlet and the outlet faces. In Figure 12, the dark gray circle represents a cap on the outlet side of the injector.

Figure 12: The Fuel Injector Model in SolidWorks

At this point, a new fluid flow simulation, called a project by SolidWorks, is created using the wizard (upper left corner of the Flow Simulation Ribbon). In the student edition of SolidWorks, the only compressible fluid available is water. Additionally, natural gas is not a fluid option either. Instead, methane is used to analyze the fluid flow through the injector because compressed natural gas is composed primarily of methane. The methane in the fluid flow analysis will also be run as incompressible, since there is no option to analyze the compressible flow of methane.
After a new project has been created by the wizard, the parameters describing the inlet and the outlet conditions must be specified. These are called boundary conditions. To create a new boundary condition, right click the Boundary Conditions heading in the design menu at the left of the SolidWorks window and select “Insert Boundary Condition”. Select the location where the boundary condition will be applied. In this case, a boundary condition is created for the interior face of the inlet cap. This boundary condition specifies the inlet pressure and temperature of methane going to the injector. The inlet pressure is set at various total pressures between 15 lbf/in$^2$ and 120 lbf/in$^2$ for various flow simulation projects because the fuel rail pressure varies between these two values. This range is well outside the pressure range where methane can be considered incompressible, but the incompressible assumption must be used due to limitations of the program. The temperature is always set at 77 °F because that is the temperature at which material values are tabulated in the Sonntag and Borgnakke thermodynamics textbook. A similar procedure is used for the outlet of the fuel injector. The pressure at the outlet is set at 14.7 lbf/in$^2$ and the temperature is set at 77 °F for all of the flow simulation projects.
because these values represent standard atmospheric conditions. The process of setting the boundary conditions can be seen in Figure 13 above.

The next step in the process is to create a goal for the fluid flow analysis. Setting a goal provides the program with a specific outcome to calculate. Right click on the “Goals” and create a surface goal. The menu that appears is shown in Figure 14 at right for reference.

Select the interior face of the outlet cap and choose “Mass Flow Rate” from the “Parameters” menu. The column at the far left of the Parameters menu allows the user to pick which values are used for convergence calculations. Selecting too many values to use for convergence dramatically slows down the calculation time, so it is important to deselect the values that are not relevant to this fuel injector calculation. Heat transfer is deselected because the injector is assumed to be adiabatic. Any values in the x- and y-directions are also deselected because the direction of flow is in the z-direction. It is especially important, however, that the mass flow rate is used for convergence because this value must converge to give an accurate resulting mass flow rate through the injector.

The project is now ready to analyze. Click the “Run” button and watch the iterations pass until the calculation converges. When the analysis completes, a report can
be generated from a template. The results of the fluid flow simulation, including the mass flow rate, can be found in this report. The method presented is repeated for a variety of pressures between 15 lbf/in$^2$ and 120 lbf/in$^2$ so that the effect of fuel rail pressure on mass flow rate can be determined.

3.4: Analytical Calculation

3.4.1: Theory

The analysis of the fuel flow rate of compressed natural gas begins with the Equation of Continuity. Basically, this means that the mass flow rate of compressed natural gas entering the fuel injector is the same as the mass flow rate exiting the fuel injector. Additionally, the mass flow rate can be related to the density of the fuel, the cross-sectional area through which it flows, and the velocity at which the fuel flows. This relationship is written as Equation 2 below [5].

*Equation 2: The Equation of Continuity (Expanded Form)*

$$\omega = \rho_i A_i V_i = \rho_e A_e V_e$$

where

$$\omega = \text{Mass Flow Rate}$$

$$\rho = \text{Fluid Density}$$

$$A = \text{Cross – Sectional Area}$$

$$V = \text{Fluid Velocity}$$

$$i = \text{Inlet}$$

$$e = \text{Exit}$$
It is assumed that as the fuel passes through the orifice in the fuel injector, the mass flow rate remains constant. For any point in the fuel injector, the equation of continuity can be reduced to Equation 3.

**Equation 3: The Equation of Continuity (Reduced Form)**

\[ \omega = \rho AV \]

where

- \( \omega \) = Mass Flow Rate
- \( \rho \) = Fluid Density
- \( A \) = Cross – Sectional Area
- \( V \) = Fluid Velocity

Assuming that compressed natural gas can be approximated as an ideal gas, the density of CNG can also be determined using the Ideal Gas Law, shown as Equation 4 below [5].

**Equation 4: The Ideal Gas Law**

\[ \rho = \frac{P_0}{RT_0} \]

where

- \( \rho \) = Fluid Density
- \( P \) = Stagnation Pressure (absolute)
- \( R \) = Gas Constant
- \( T \) = Stagnation Temperature (absolute)

At a certain point in the system, the fuel has a velocity of zero. At this point, the fuel has no kinetic energy, only internal energy. This point is called the stagnation point, and the temperature at this point is the stagnation temperature. The stagnation
temperature is higher than the static temperature because some of the energy that would have increased the temperature of the fuel is converted to kinetic energy. The stagnation temperature is related to the static temperature by the following relationship, presented as Equation 5 [3].

\[ T_0 = T + \frac{V^2}{2c_p} \]

where

\( T_0 = \) Stagnation Temperature (absolute)

\( T = \) Static Temperature (absolute)

\( V = \) Velocity

\( c_p = \) Constant Pressure Specific Heat

Another important relationship is the constant pressure specific heat \( c_p \). For an ideal gas, the constant pressure specific heat can be related to the specific heat ratio \( k \) and the ideal gas constant \( R \). This relationship is defined as shown in Equation 6 below [3].

\[ c_p = \frac{kr}{k - 1} \]

where

\( c_p = \) Constant Pressure Specific Heat

\( k = \) Specific Heat Ratio

\( R = \) Ideal Gas Constant
Additionally, the speed of sound, \( a \), is defined as a relationship between the specific heat ratio \( k \), ideal gas constant \( R \), and temperature \( T \) of the fuel. This is shown as Equation 7 [3].

\[ \text{Equation 7: Definition of the Speed of Sound} \]

\[ a = \sqrt{kRT} \]

where

\( a = \text{Speed of Sound} \)

\( k = \text{Specific Heat Ratio} \)

\( R = \text{Ideal Gas Constant} \)

\( T = \text{Temperature (absolute)} \)

Combining Equations 1, 3, 4, 5, 6, and 7, the mass flow rate can be determined by Equation 8. [3]

\[ \text{Equation 8: Mass Flow Rate Equation for Compressible Fluids} \]

\[ \omega = A \left( \frac{k}{R} \right) \frac{P}{\sqrt{T_0}} \frac{M}{\sqrt{1 + \frac{k - 1}{2} M^2}} \]

where

\( \omega = \text{Mass Flow Rate} \)

\( A = \text{Cross - Sectional Area} \)

\( k = \text{Specific Heat Ratio} \)

\( R = \text{Ideal Gas Constant} \)

\( P = \text{Static Pressure (absolute)} \)

\( T_0 = \text{Stagnation Temperature (absolute)} \)

\( M = \text{Mach Number} \)
It is also necessary to find the Mach number of the moving compressed natural gas. Since the static pressure and the stagnation pressure are known, it is useful to use an equation relating the pressure ratio to the Mach number. Such an equation is written below in two forms as Equation 9 [3].

\[ \frac{P_0}{P} = \left(1 + \frac{k - 1}{2} M^2\right)^{\frac{k}{k-1}} \]

\[ M = \sqrt{\left(\frac{2}{k-1}\right) \left(\frac{P_0}{P}\right)^{\frac{k-1}{k}} - 1} \]

where

\( P_0 = \text{Stagnation Pressure (absolute)} \)

\( P = \text{Static Pressure (absolute)} \)

\( k = \text{Specific Heat Ratio} \)

\( M = \text{Mach Number} \)

Since the Mach number through orifice will never be greater than \( M = 1 \), Equation 9 can also be used to determine the maximum stagnation pressure beyond which there will be no increase in mass flow through the fuel injector. This is known as the critical pressure, and by letting \( M = 1 \) and rearranging Equation 9, can be found by Equation 10 below [3].
Equation 10: The Critical Pressure

\[ P_c = P \times \left(1 + \frac{k - 1}{2}\right)^{\frac{k}{k-1}} \]

where

- \( P_c \) = Critical Pressure (absolute)
- \( P \) = Static Pressure (absolute)
- \( k \) = Specific Heat Ratio
- \( M \) = Mach Number

3.4.2: Assumptions

For this calculation method, multiple assumptions must be made. The fuel injector was considered to be adiabatic and the coefficient of discharge was assumed to be unity for convenience. Later iterations to the calculation method can determine a proper value for the coefficient of discharge based on the complex geometry of the orifices. Fuel flow through the orifices was considered to be isentropic. Additionally, the path through the injector is assumed to be frictionless and one-dimensional. One-dimensional fluid flow assumes that the flow path of the fluid is approximately linear. This calculation method was formulated before the injector had been cut in half. The actual flow path of the compressed natural gas through the injector was unknown, so it was imagined to be similar to the nearly linear flow path seen in Figure 1 above. Also, the temperature inside the tank was assumed to be the same as the temperature outside the tank. The fuel rail pressure was approximated as a stagnation pressure because of the length of fuel pipe between the pressure regulator and the fuel injector. The injector outlet pressure was also assumed to be a static pressure at atmospheric conditions.
3.4.3: Sample Calculation

To better illustrate the process of calculating the mass flow rate through the fuel injector based on the pressure ratio, an example calculation is provided below. A table of variables, Table 1 below, is also provided to summarize the parameters of this example problem.

Table 1: Values for the Sample Calculation of Mass Flow Rate and Critical Pressure

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$</td>
<td>Static Pressure (absolute)</td>
<td>$14.69594 \frac{lb}{in^2}$</td>
</tr>
<tr>
<td>$P_0$</td>
<td>Stagnation Pressure (absolute)</td>
<td>$25 \frac{lb}{in^2}$</td>
</tr>
<tr>
<td>$T_0$</td>
<td>Stagnation Temperature (absolute)</td>
<td>$537 , ^\circ R$</td>
</tr>
<tr>
<td>$R$</td>
<td>Ideal Gas Constant</td>
<td>$79.1 \frac{lb \cdot ft}{lbm \cdot ^\circ R}$ [6]</td>
</tr>
<tr>
<td>$k$</td>
<td>Specific Heat Ratio</td>
<td>$1.27$ [6]</td>
</tr>
<tr>
<td>$A$</td>
<td>Orifice Area</td>
<td>$0.0036 , in^2$</td>
</tr>
<tr>
<td>$g_c$</td>
<td>Constant $g_c$</td>
<td>$32.174 \frac{lb \cdot ft}{lbm \cdot s^2}$</td>
</tr>
</tbody>
</table>

The values from Table 1 are inserted into Equation 9. The Mach number of the compressed natural gas flowing through the orifice of the fuel injector when the fuel rail pressure is $P_0 = 25 \frac{lb}{in^2}$ is calculated below.
\[ M = \sqrt{\left(\frac{2}{k - 1}\right) \left(\left(\frac{P_0}{P}\right)^{\frac{k-1}{k}} - 1\right)} \]

\[ M = \left(\frac{2}{1.27 - 1}\right) \left(\frac{25 \text{ lbf}/\text{in}^2}{14.69594 \text{ lbf}/\text{in}^2} \right)^{\frac{1.27 - 1}{1.27}} - 1 \]

\[ M = 0.9412 \]

Note that if the Mach number was greater than \( M = 1 \), then the Mach number was reduced back to \( M = 1 \). This is because the Mach number cannot exceed \( M = 1 \) through the smallest cross-section of its flow.

Using the Mach number (or the adjusted Mach number), the mass flow rate for this sample calculation is shown below in both lbm/s and grams/s. Equation 8 was used.

\[ \omega = A \sqrt{\frac{k}{R}} \frac{P}{\sqrt{T_0}} M \sqrt{1 + \frac{k - 1}{2} M^2} \]

\[ \omega = (0.0036 \text{ in}^2) \left(\frac{1 \text{ ft}}{12 \text{ in}}\right)^2 \left(\frac{1.27}{79.1 \text{ lbf}/\text{ft}/\text{lbm}^\circ R}\right) \left(\frac{14.69594 \text{ lbf}/\text{in}^2}{\sqrt{537 \circ R}}\right) \]

\[ * \left(\sqrt{\frac{32.174 \text{ lbf}/\text{ft}}{\text{lbm}/s^2}}\right) (0.9412) \left(\sqrt{1 + \frac{1.27 - 1}{2} 0.9412^2}\right) \]

\[ \omega = 0.0016 \frac{\text{lbm}}{s} = 0.7411 \frac{\text{grams}}{s} \]

The critical pressure is also calculated as a way of checking the mass flow rate results using Equation 10.
\[
P_c = P \left(1 + \frac{k - 1}{2}\right)^{\frac{k}{k-1}}
\]

\[
P_c = 14.69594 \frac{\text{lbf}}{\text{in}^2} \left(1 + \frac{1.27 - 1}{2}\right)^{\frac{1.27}{1.27-1}}
\]

\[
P_c = 26.6613 \frac{\text{lbf}}{\text{in}^2}
\]

Any fuel rail pressure over \( P_c = 26.6613 \frac{\text{lbf}}{\text{in}^2} \) will not increase the mass flow rate of compressed natural gas through the fuel injector.

3.5: Experimental Solution

One of last year’s Capstone teams, the Injector Bench team, performed testing on the compressed natural gas fuel injector. Pressurized CNG was directed through the fuel rail, then through the injector. After passing through the Delphi Multec Compressed Natural Gas Injector, the fuel was emptied into a sealed flow pipe. A pressure transducer (Omega PX302-015G) measured the pressure in the flow pipe before and after compressed natural gas was injected into the flow pipe. From this, the mass flow rate of the fuel...
was calculated. A drawing of the apparatus is shown in Figure 15 above [1]. For more information, please see the Injector Bench’s Final Report and Mech. Lab. III Report, which are cited in the References section of this report.
4.1: SolidWorks Flow Simulation

4.1.1: Results

A graph of the SolidWorks Flow Simulation results is presented as Figure 16 below. As shown, at a stagnation pressure of 15 lbf/in$^2$ (absolute), the mass flow rate of methane through the fuel injector is 0.017 grams/s. At 120 lbf/in$^2$ (absolute), the mass flow rate is 0.726 grams/s. Between these two points, as the fuel rail pressure increases, the mass flow rate increases nearly linear fashion. There is a slight variation in the results that prevents the results from following a straight line between the two extrema, but the deviation from a straight line is not very significant.
4.1.2: Interpretation of Results

The results of the SolidWorks Flow Simulation may appear linear because the orifice area through which the fuel flows is very small, making the mass flow rate very small as well. If the orifice area had been larger, the mass flow rate would also have been larger and the trend in fuel flow rate as a function of pressure may have been more evident. The small deviations of the data from a linear relationship appear to be due to rounding issues, given that all the outputs of the mass flow rate were very small, and it is difficult to precisely determine such small values.

Note that, as the fuel rail pressure increases, the mass flow rate continues to increase as well, even when the pressure is greater than the critical pressure. This indicates that the model did not take into account any flow choking, which makes sense because incompressible fluid flow does not experience choking. The fact that the fluid had to be modeled as incompressible in SolidWorks Flow Simulation is a significant limiting factor of this model.

4.2: Analytical Calculation

4.2.1: Results

Using the calculation method outlined in the Analytical Calculations subsection, mass flow rates of compressed natural gas were calculated in pounds per second. The results were converted to grams per second for comparison with the experimental data taken last year. The mass flow rates were also graphed as a function of stagnation pressure, and shown in Figure 17 below. Figure 18 shows the subsection of Figure 17 for the mass flow rate that results from pressures between 15 lbf/in$^2$ and 27 lbf/in$^2$. As the
pressure in the fuel rail increases from 15 lbf/in² to 26.7 lbf/in², the mass flow rate increases sharply from approximately 0.12 grams/s to 0.79 grams/s. The increase in mass flow rate begins to slow as the pressure approaches 27 lbf/in². At 26.7, the mass flow rate quickly evens to a constant 0.79 grams/s regardless of any further increase in pressure.

![Analytical Calculation Results](image.jpg)

Figure 17: Analytical Calculation Results - Mass Flow Rate vs. Pressure
4.2.2: Interpretation of Results

As expected, as the pressure in the fuel rail increases to a certain point, the mass flow rate also increases. At 26.7 lbf/in², the mass flow rate stops increasing. This corresponds to the critical pressure, which was calculated with Equation 10 above. At this pressure, the Mach number is $M = 1$ and cannot increase any further. Thus, the mass flow rate cannot increase as well. The flow of compressed natural gas through the fuel injector is choked when the fuel rail pressure is 26.7 lbf/in². For comparison, a plot similar to Figure 17 is shown as Figure 19 below. In Figure 19, a scenario is imagined in which the fluid is modeled as incompressible and the flow does not choke. A simple equation was used to determine the mass flow rates, shown as Equation 11 below [7].
Equation 11: Mass Flow Rate Equation for Incompressible Fluids

\[ \omega_{\text{incomp}} = \rho A \sqrt{\frac{2 (P_0 - P)}{\rho}} \]

In this imagined scenario, the Mach number of the fuel flow through the orifice is allowed to exceed \( M = 1 \). The blue line in Figure 19 indicates the actual results, while the red line indicates the imagined scenario. The red line appears to follow the shape of a square root function.

Figure 19: Comparison of Compressible and Incompressible Mass Flow Rates
4.3: Experimental Results

4.3.1: Results

From last year’s Capstone team, the mass flow rates of compressed natural gas through the fuel injector at several fuel rail pressures, pulse widths, and duty cycles were found. Selected results are shown in Figures 20 and 21 below [8]. Figure 20 shows the mass flow rate in grams per second as a function of duty cycle percentage at fuel rail pressure of 30 lbf/in$^2$ gage (44.7 lbf/in$^2$ absolute) with an injector pulse width of 20 ms. At a duty cycle percentage of 5%, the mass flow rate is approximately 0.74 grams per second. As the duty cycle percentage increases to 85%, the mass flow rate increases to about 1.08 grams per second. For comparison, Figure 21 shows the mass flow rate in grams per second as a function of duty cycle percentage at fuel rail pressure of 100 lbf/in$^2$ gage (114.7 lbf/in$^2$ absolute) with an injector pulse width of 20 ms. At a duty cycle percentage of 5%, the mass flow rate is approximately 2.16 grams per second. As the duty cycle percentage increases to 85%, the mass flow rate appears to increase in a logarithmic shape to about 2.46 grams per second.
Figure 20: Experimental Results - Mass Flow Rate at 30 psig [8]
Representative values were taken from the previous year’s results for ease of comparison with the results found analytically and through SolidWorks since pulse widths and duty cycles were not modeled. The representative value for a given pressure was the mass flow rate value at a duty cycle of 85%, where the fuel injector was open for 85% of the test duration. This is the closest situation from the experiment performed to the constantly open fuel injector that was modeled in SolidWorks and used for analytical calculations. The representative value for 30 lbf/in² (gage) is 1.08 grams/s, and for 100 lbf/in² (gage), 2.46 grams/s.
4.3.2: Interpretation of Results

From last year’s results, it can be seen that the duty cycle does seem to have some effect on the mass flow rate. The duty cycle percentage indicates the percent of time that the orifices are clear for the fuel to flow through them. In both the 30 lbf/in$^2$ (gage) and the 100 lbf/in$^2$ (gage) tests, the mass flow rate of fuel through the injector increased as the duty cycle percent increased. In both cases, the duty cycle percentage had an influence of less than 0.35 lbf/in$^2$. Since the mass flow rates are so small to begin with, this change in duty cycle had a significant effect on the mass flow rate of the fuel through the orifices.

The representative values of mass flow rate also differ substantially from each other. The previous year’s Capstone team found that the mass flow rate did, in fact, continue to vary with pressure at high pressures, which is surprising considering the compressed natural gas is assumed to be compressible. One important aspect to note about the previous year’s experiment is that the temperature inside the flow pipe was not determined. As the pressure drops as the compressed natural gas expands from the fuel rail into the flow pipe, the temperature of the compressed natural gas also decreases. Changing the pressure and the temperature affects the density of the compressed natural gas. If the density is to be used in a mass flow rate calculation, it must be determined accurately, meaning both pressure and temperature must be considered. The fact that there was no temperature-measuring device in the flow pipe indicates that the mass flow rate results might not be very accurate.
CHAPTER 5: VALIDATION AND CONCLUSIONS

The three sets of results, one for the SolidWorks Flow Simulation, one for the compressible flow calculation, and one for the experimental results from last year’s Capstone team, along with an additional curve for an incompressible flow calculation, are shown in below in Figure 22. The blue line indicates the SolidWorks Flow Simulation solution, the red line indicates the compressible flow calculation, the purple line indicates what the mass flow rate would be if the fluid were incompressible, and the two green data points indicate the results from the experiments performed by last year’s Capstone team.

![Comparison of Results](image)

Figure 22: Comparison of Results - Mass Flow Rate vs. Pressure
Of the three sets of results from this report, the SolidWorks Flow Simulation method provided the lowest mass flow rate. This could be due to the fact that methane was used as the fuel flowing through the injector instead of compressed natural gas. More significantly, the lower mass flow rates from the SolidWorks model could be attributed to the fact that the SolidWorks model incorporated frictional losses and losses attributed to the minor losses that occurred when the compressed natural gas encountered the four 90° turns in the flow path. The analytical calculation did not incorporate frictional losses and assumed that the flow was one-dimensional. The highest mass flow rate was found from the experimental results. In fact, the experimental result for mass flow rate at a fuel rail pressure of 100 lbf/in² gage is much higher than the results for the compressible flow calculation and the SolidWorks Flow Simulation. This could be due to imprecise measurement of pressure in the flow pipe, or the fact that the fuel pipe was so large, causing only a small change in pressure when fuel was introduced.

The data from the three types of mass flow rate determination suggest that the mass flow rate should not exceed 0.8 grams/s, regardless of the fuel rail pressure, because the compressible flow calculation and the SolidWorks Flow Simulation solution are on the same order of magnitude. It appears that the experimental solution greatly overestimated the amount of fuel flow through the injector, though more experiments are necessary to determine the mass flow rate at more pressures.
CHAPTER 6: FUTURE WORK

This report provides the basis for much more future work pertaining to the determination of the mass flow rate of compressed natural gas through the Delphi Multec CNG Injector. Future Capstone teams could invest in a version of SolidWorks that contains compressed natural gas as a fluid in the materials database. An alternative option is to invest in a copy of Autodesk CFD (Computational Fluid Dynamics) that includes the ability to compute compressible flow for compressed natural gas. Once proper models have been established, future groups could incorporate the effects of varying the pulse width and duty cycle of the injector. From experimental results, it can be seen that these do have an effect on the mass flow rate, though that effect is not yet clear. Additionally, the effect of creating pressure waves from rapidly blocking and unblocking the orifices could be explored.

Improvements to the analytical calculation method could also be made. Most notably, future teams could incorporate the minor losses encountered as the compressed natural gas travels around four sharp 90° turns in the flow path. Frictional losses and a coefficient of discharge could also be included in the calculation.

Most importantly, future teams could re-run the experiment performed by last year’s Capstone team at a larger variety of pressures to see what kind of relationship the experimental results actually form. Changes to the experiment could also be made, such as using a smaller volume flow pipe to better detect the small changes in pressure that result from injecting a small amount of fuel into a large flow pipe. Future teams could also use a larger flow tank and let the fuel injector run for a longer period of time. This would reduce any variation in mass flow rate due to the start-up and shut-down of the
injector. One change that is very important for future teams to implement is to install a thermocouple or other temperature-sensing device in the flow pipe. This allows for proper calculation of the density of the compressed natural gas so that an accurate value of mass flow rate can be calculated. An experiment could also be designed using a mass flow meter to more directly measure the mass flow rate through the injector, though this is significantly more expensive.

Ultimately, future teams could use improved models to determine how fuel rail pressure and engine speed affect the mass flow rate of fuel from the injector. Fuel curves could be compiled and the ECU reprogrammed so that the CNG snowmobile can run efficiently on compressed natural gas.
BIBLIOGRAPHY


APPENDICES

Appendix A:  Glossary

Appendix B:  The Delphi Multec Compressed Natural Gas Injector
Appendix A: Glossary

**Absolute Pressure** – A pressure measured with reference to a vacuum, labeled with units of psia. The absolute pressure of the atmosphere at sea level under standard conditions is 14.7 psia.

**Adiabatic** – A process in which heat transfer to or from a control volume does not occur.

**Atomize** – In fuel injection systems, to turn liquid fuel into a very fine mist so that it mixes well with the air and combusts evenly.

**AutoCAD** – A two- and three-dimensional computer aided drafting and design software.

**Autodesk CFD (Computational Fluid Dynamics)** – A computational fluid dynamics and heat transfer software.

**Autodesk Inventor** – A mechanical design and three-dimensional CAD software that allows users to create and test products, similar to SolidWorks [9].

**Choking** – In fluid dynamics, the situation in which the mass flow rate through a nozzle cannot increase further by increasing the upstream pressure if the downstream pressure is held constant. The velocity of the fluid is limited by the fact that the Mach number of the fluid cannot exceed $M = 1$ through the smallest cross sectional area.

**Coefficient of Discharge** – The ratio of the actual fluid flow through an orifice to the ideal flow through the orifice. The discharge coefficient is based primarily on the geometry of the orifice.

**Compressed Natural Gas (CNG)** – An alternative fuel source to gasoline and diesel. CNG is mainly composed of methane [10].

**Compressible** – A fluid whose density increases as the pressure on the fluid increases.
**Computational Fluid Dynamics** – A method of numerical analysis based on the Navier-Stokes equations used to study fluid dynamics.

**Critical Pressure** – The upstream pressure that, if raised, would not cause the mass flow rate of a fluid to increase through an orifice given that the downstream pressure is held constant.

**Duty Cycle** – The percent of the period of an on-off cycle during which the signal is on. For this paper, the duty cycle refers to the percent of time the fuel injector is open, allowing fuel to pass through the injector. For a descriptive image relating duty cycle, pulse width, and the period of a cycle, please see Figure 23 below [11].

![Duty Cycle Graph](image)

**Figure 23**: Graphical Description of Duty Cycle, Pulse Width, and Cycle Period [11]

**Engine Control Unit (ECU)** – The computer on a vehicle that analyzes parameters and controls the electrical system on the vehicle by sending an electric current to open and close the fuel injector.

**Flow Pipe** – In the experimental solution performed by last year’s Capstone team, the container onto which the fuel flowed after it had passed through the injector.
pressure inside this vessel was measured to determine the amount of mass that passed
through the injector in a certain amount of time.

**Frictional Losses** – Mass flow rate losses associated with friction between the injector
channel surface and the fuel itself.

**Fuel Flow Curve** – A graphical relationship between the fuel rail pressure and the mass
flow rate of fuel that passes through the injector.

**Fuel Injector** – A device that delivers a specific amount of fuel from the fuel rail to the
intake manifold of a vehicle, generally atomizing the fuel as it passes through the device.

**Fuel Rail** – A pipe that supplies fuel to the fuel injector at a specific pressure.

**Gage Pressure** – A pressure measured with reference atmospheric pressure under
standard conditions, labeled with units of psig. The absolute pressure of the atmosphere
at sea level under standard conditions is 0.0 psia.

**Incompressible** – A fluid whose density does not increase significantly as pressure on
the fluid increases.

**Injector Shell** – The stationary part of the fuel injector, which includes the inlet, injector
channel, orifice plate, and outlet of the injector. The plunger is not included as part of the
injector shell.

**Intake Manifold** – The part of an engine into which the fuel is injected. The intake
manifold provides the chamber for the fuel and air to mix before it passes to the cylinders
of the engine.

**Isentropic** – A process during which the entropy of the working fluid does not change.

**Mach Number** – The ratio of the speed of a moving fluid to the speed of sound of that
fluid.
**Minor Losses** – Mass flow rate losses associated with bends and corners in the flow path of a fluid.

**Octane Rating** – A description of the quality of the fuel. Fuels with higher octane ratings can withstand more compression before ignition, which reduces engine knocking.

**One-Dimensional Flow** – An assumption that the flow path of a fluid is approximately linear.

**Orifice** – An opening through which fluid can flow. In this paper, the term refers to the four small, oblong openings through which the compressed natural gas exits the fuel injector.

**Plunger** – The moveable piece inside the injector that is pulled up the injector channel by an induced magnetic field to let compressed natural gas flow through the injector and is pushed closed by a spring to cover the orifices and cut off the fuel flow.

**Pressure Ratio** – The ratio of the fuel pressure in the fuel rail to the pressure in the intake manifold.

**Pressure Transducer** – A device that converts pressure data to an electrical signal for digital recording. The signal can later be converted back to pressure readings.

**Pulse Width** – The period of time during an on-off signal cycle during which the signal is on. The pulse width is equal to the duty cycle percentage times the frequency of the signal cycle. For a descriptive image relating duty cycle, pulse width, and the period of a cycle, please see Figure 23 above.

**SolidWorks** – A computer aided design software used for creating and analyzing two-dimensional drawings and three-dimensional parts and assemblies.
SolidWorks Flow Simulation – A computational fluid dynamics package in SolidWorks that enables users to study fluid dynamics and heat transfer in and around created parts.

Stagnation – When referring to pressure or temperature, indicates that the reference to which the value is measured is a still working fluid. The kinetic energy effects on pressure and temperature are accounted for. Also called “total” pressure or temperature.

Static – When referring to pressure or temperature, indicates that the reference to which the value is measured is a moving working fluid. The kinetic energy effects on pressure and temperature are not included.

Stoichiometric – In chemistry, the balanced state in which all the reactants are used during a reaction with no excess at the end of the reaction.

Thermocouple – A device used to measure temperature digitally.
Appendix B: The Delphi Multec Compressed Natural Gas Injector

Delphi Multec® Compressed Natural Gas Injector

The Delphi Multec® Compressed Natural Gas (CNG) Injector is another advanced technology in Delphi's portfolio of multi-port fuel injectors. It offers engine manufacturers excellent cost efficiency and robustness. The injector is optimized for compatibility with CNG and other alternative fuels to harness their significant greenhouse gas emissions reduction potential. Its tailored design allows efficient engine operation with low energy density fuel systems that require high gas volumes and flow velocities. The injector can be operated with a conventional gasoline engine control module, enabling low cost implementation.

Delphi also offers manufacturers CNG-compatible mono-fuel, bi-fuel and tri-fuel engine management systems that include injectors, engine control modules, tailored software and algorithms, high energy ignition coils, electronic throttle control and exhaust sensors.

- **CNG Benefits**
  - Lower fuel cost significantly reduces consumer operating expense
  - Facilitates CO2 reduction by up to 25% and zero particulate emissions

- **Injector Benefits**
  - Optimal fuel metering: high flow capacity at pressures up to 9 bar, superior linear flow range, accuracy, and stability
  - Low operating noise
  - High wear resistance, particularly in lubricant-free gaseous fuel operation, up to 400 million cycles with CNG
  - Compatible with conventional engine controllers
  - High impedance injector allows use of lower cost "saturated switch" injector driver

- **Typical Applications**

  The Delphi Multec Compressed Natural Gas Injector is designed specifically for port fuel injection engines that operate on gaseous fuels, including: compressed natural gas, propane, and liquefied petroleum gas. It is suitable for gasoline bi-fuel engine programs.

- **Availability**

  The Delphi Multec Compressed Natural Gas Injector is in serial production. Manufacturers should contact Delphi for further information and engineering samples.

- **Performance Advantages**

  The Delphi Multec Compressed Natural Gas Injector is compatible with conventional port fuel injection engine controllers equipped with saturated switch drives, which help reduce system cost by eliminating the need for a secondary or higher cost, specialized engine controller.
Delphi’s proven port fuel injection technology and our injection systems engineering expertise were applied in the development of our CNG injector to help optimize performance, reliability and durability.

- The Delphi Advantage

Delphi has produced hundreds of millions of gasoline fuel injectors over the years for customers around the world. That vast experience has led to product and manufacturing process improvements which have helped eliminate contamination-related failures and provided other quality and cost advantages. Delphi’s in-depth knowledge of automotive systems and the combustion process help optimize injector performance.

As a global leader in engine management systems technology, Delphi can help manufacturers meet emissions requirements, improve fuel economy and enhance performance. Delphi is a source for high value solutions and our systems approach encourages collaboration. And, Delphi has a thorough understanding of automotive markets around the world and a global network of resources.
Erin E. Eldridge was born in Maine in 1993. She was raised in Maine and graduated as salutatorian from Brunswick High School in 2012. She attended the University of Maine in Orono, Maine. She graduated *summa cum laude* in 2016 with a major in mechanical engineering and a minor in mathematics. Erin plans to work for SUPSHIP, a division of NAVSEA, in Bath, Maine after graduation.