Fuel Tank Full-Fill Considerations

Natural Gas Vehicle Technology Forum
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Gas Technology Institute
List of Topics

> Background
  - Defining a full-fill
  - Defining the issues in gaseous fueling
  - Defining the impact

> Discuss temperature compensation

> Discuss barriers/solutions to better dispenser controls – CEC Project

> Discuss additional improvements
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Gas Technology Institute Overview

Natural Gas Research and Development Focus

> Staff of 300
> 350 active projects
> 1,200 patents; 500 products
Defining a Full-Fill

> Full-fill: 3600 psi (settled P) at 70 °F (settled T)

> Temperature compensation: Correcting for pressure changes due to temp changes in the gas
  — “Full” Density: 1800 psi at -40°F and 4500 psi at 130°F

> Heat of compression: Pressure rise causes temp in cylinder to rise quickly (makes fast-filling difficult)
  — Temporarily high T and P causes fueling procedure to stop with less than “full” density
Defining a Full-Fill

> Dispenser control strategies determine stopping target pressure (typically pressure table based on ambient temp)

> Under many conditions fills do not reach “full” density
  – Sometimes 20% - 30% less than optimal

> Driver’s perception of “full” is important
  – Pressure is a poor indication of “full”
  – Temperature compensated fuel gauge
Defining the Issues

> High ambient temperatures and amount of gas in cylinder are major contributors to under-filling
  — Though many other factors influence final density

> Industry direction is demanding better solutions
  — Cylinders are larger (>150 GGEs on-board)
  — Fills are getting faster (high flow dispensers)
  — Success of industry leads to higher expectations (OEMs and very large fleets) and higher impacts for safety/reliability/consistency

> Safe fills are essential to industry growth
Defining the Impact

> Significant under-filling affects major issues in the industry:

- Cost (up to 10% of conversion cost)
- Range (100’s of miles – 30 GGE “missing” on HD trucks with 150 GGE of storage)
- Weight/Space (critical for important markets)
- Fuel economy (impacts environmental, cost, and range concerns)
- Customer Satisfaction – misunderstandings lead to bad experiences and disappointments
Primary Safety Concern: Temperature Compensation

> Temperature Compensation: For a given gas composition, there is a constant density that equals 3600 psi at 70 °F (~0.21 g/cm³ for typ. NG)

> Safety is primary concern—dispensers use of temperature compensation is important
  ─ Without compensation a fill can occur at high pressures in very cold conditions resulting in over-filling
  ─ CVEF white paper defines issue and best practices
  ─ Accountability and verification is key

> CSA NGV 4.3 – Tasked with addressing this issue
  ─ Initial topic: Defining settled pressure at various temps
Pressure related to fuel composition

> Gas composition impacts temp comp. pressure

> GM chart uses pressure limits for worst case conditions

> Difficulties on mandating max. settled pressures

> Temp comp. vehicle gauge could help

Temperature Compensated Fill Chart

Using two “extreme” Natural Gas available/measured compositions – one cleaner (> 97 mol% CH₄) and the other with ~ 75 mol% CH₄

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<th>Pressure (psia)</th>
<th>Density (g/cm³)</th>
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Conservative approach: maximum allowable fill pressure corresponding to worst case scenario

Anne Dally and Richard Krentz. “Compressed natural gas temperature compensated pressure fill”
Full-Fills: Optimized Temperature Compensation

> Temperature compensation is also important part of full-fill considerations but only one side of the issue

> Maintaining safe limits for station and vehicle (i.e. preventing over-filling) while optimizing fill (i.e. reducing under-filling) presents significant challenges

> Utilizing “target” stop pressure estimates without accounting for additional factors will not meet goals of safety and customer satisfaction
Full-Fills: System Design Parameters

> Safe operation demands code compliance (ANSI NGV2, NFPA 52, others)

> Major design parameters include:
  - Max. settled pressure of 3600 psi at 70 °F
  - Max. over-pressurization limit 125% = 4500 psi
  - Max. temperature of cylinder during fill = 180 F
  - Max. pressure relief in dispenser = 4500 psi (4300 psi, practically)

> Practical operations of station reduce available gas supply
Barrier: Target Stopping Pressure

Target (End of Fill) Tank Pressures

- SRV Set point (4500 psig)
- FILL SETTLED
- 25% FILL
- 50% FILL
- 75% FILL
- 100% FILL
- Fill Limit

Area of unobtainable tank pressures (due to SRV set point)
Area of unobtainable tank pressures (due dispenser cut-off pressure to avoid SRV lifting/weeping)
Area of unobtainable tank pressures (due hydraulic losses in the filling circuit (hose and vehicle))
Target Settled Pressure

ANGI Energy Systems
Barrier: Target Stopping Pressure

Fill Completeness Forecast

Completeness of Fill (% of Compensated Target)

Based on:
- 4300 psig dispenser clip
- 200 psig drop in hose and vehicle fueling circuit

Ambient Temp. (deg F)
Station Control Improvements

> Several “solutions” do exist to improve fueling performance

> First, discuss dispenser controls/algorithms

> CEC funded GTI under PON-14-502 – Infrastructure Improvement Research for Natural Gas Fueling Stations

> Major project partner: ANGI

> Builds on past experience and successes
  – Accufill mass-based fueling protocol
GTI’s Current CEC Project

The goals of the proposed project are:

- Develop an advanced fueling control method (including initial characterization step)
- Design a test system that delivers improved fills
- Validate and quantify benefits
- Demonstrate improvements in cost-effectiveness and efficiency of fueling infrastructure and vehicle costs

Looking at the issues that are in station’s control (i.e. non-communications)

- Largest, most immediate impact for existing industry
GTI’s Current CEC Project

> Concern is that dispenser pressure tables alone are trying to solve a complex problem with a simple solution – lead to unacceptable under-filling

> Calculation of internal energy based on variety of variables (known, calculated, and bounded)

> Accurate control requires compensation for:
  – Initial cylinder gas pressure, temperature, composition
  – Initial station gas pressure, temperature, composition
  – Cylinder volume and thermal resistance (varies by type)
  – Flow rate of gas
  – Ambient Temperature
GTI’s Current CEC Project

> Initial modeling has shown important parameters and consistent results with past testing
  — Simulink modeling to calculate internal energy in cylinder

> Limited initial testing of baseline dispensers has shown that 20% under-filling occurs

> Test data from large fleet has shown significant under-filling even when using customer controlled fill settings

> Design of Experiments: evaluate all variables and quantify their importance

> Continued modeling and testing over the next year
Potential “Solutions” (or at least advancements)

- Controls/Algorithm improvements
  - Additional input/data/testing will be needed
  - Potentially leads to standardized control process

- Station equipment improvements – compressor, valve panels, dispensers
  - Improve hydraulic losses/pressure drops and improve flow, redundant pressure transducers to decrease error

- Increase pressure limit on dispenser PRDs
  - PRD setting at ~5000 psi would allow stations to utilize existing gas pressure
Potential “Solutions” (or at least advancements)

> Pre-cooling (i.e. heat exchanger/chiller to lower temperature of supply gas)
  – Done in some situations today; tied to optimized algorithm
  – Disadvantages include capital and operating costs

> Communications (active or passive)
  – Cylinder volume, cylinder type, gas temperature, gas pressure from vehicle to dispenser would provide benefit
  – Disadvantages include existing vehicles, timing, etc.

> Vehicle controlled fueling termination
  – Control valve stops fill based on vehicle pressure and temp
  – Control/liability passes to vehicle
Potential “Solutions” (or at least advancements)

> Vehicle cylinder type can improve heat removal/loss
  - Type IV cylinder is great insulator
  - All other cylinder types have better thermal properties (i.e. provide heat sink and increased conduction)
  - Unclear how effective heat removal is during fast-fill and doesn’t lead to industry wide solution

> Improve “low-end” pressure limits
  - Minimum fuel rail pressure and supply regulator droop = ~200 – 400 psi (5-10% “stranded” gas)
  - Engine/Injector operability limitations
  - Improved equipment on-board vehicle

> Additional improvements…
Thank you!
Backup slides
Dispenser Improvement Opportunities

There are still several aspects of vehicle and dispenser design which could be modified to further improve the fueling experience.

> Change the tank design and/or modify the code to eliminate the 4500 PSIG restriction

> Inject cool gas into the cylinder (at temperatures below ambient)

> Improve algorithms
  - Incorporate validated heat of compression factors that properly account for temperature of injected gas etc.
  - Eliminate calculation errors
  - Reduce instrumentation error

> Further reduce hydraulic losses in the hose components and on the vehicle
Additional Equipment Improvement Opportunities

- Select the appropriate dispenser design based upon the fueling application
- Reduce the hydraulic losses within the dispenser and hose assemblies by utilizing high flow, low pressure drop components; ANGI has standardized on full flow activated ball valves and tubing with a minimum 1" diameter
- Incorporate the appropriate fueling strategy & algorithm. Percentage of fill before reaching vehicle limitations is affected by the following
  - Initial vehicle tank pressure
  - Tank PRV set point
  - Heat of compression & ambient conditions
  - Hydraulic losses in filling circuit (dispenser & vehicle)

Valve Panels

Compressor  Site & Vehicles
Potential Solutions

- Pre cooling gas before the gas enters the vehicle. (Expensive and high maintenance)
- Redundant pressure transducers in the dispenser to provide a more precise measurement of the filling process.
- Raising the relief valve pressure in the dispenser to 5000 psi.
- Tank manufactures using realistic numbers and volumetric numbers that account for the limitations of the technology today. (Useable volume)
- Establishing an industry protocol to measure internal tank pressure and temperature when available.
Example: Natural Gas

NGV Fuel Storage Characteristics

![Graph showing density vs pressure for different temperatures. The graph indicates a 50°F temperature rise results in 17% less density.]

-10 F
30 F
70 F
10 F
130 F

50°F Temperature Rise Results in 17% Less Density
Example: Natural Gas

Cylinder temperature is a function of the change in injected gas mass, initial pressure, and cylinder volume.
When it comes to Temperature…location matters

Example: Type 2 (Steel) – Natural Gas (3000 psig fill pressure)
GTI CHARGE Model

> Modeling Tool
  - Characterizes Dynamic Fast-Fill Process

> Assess Cylinders of Different Size & Construction
  - Cylinders
  - Ground Storage

> Various Starting & Ending Fill Conditions

> Used To Create Dispenser Filling Algorithms
GTI CNG AccuFill® Algorithm

> GTI developed & patented technology to address CNG temperature rise during mid-1990s

> Technology licensed to several worldwide manufacturers, but not integrated

> Provides more consistent fill performance over wide range of ambient conditions

> Tech Transfer to Commercial Dispenser(s) Design Needed.