

## **Coriolis Mass Flow Metering for the LPG Industry**

Red Seal Measurement  
1310 Emerald Rd., Greenwood, SC 29646, USA

### **Abstract**

Coriolis flowmeters first gained popularity in continuous process industries beginning approximately 25 years ago. More recently, they have been deployed successfully into Liquid and Vapor Propane application with notable success. This paper provides background on the theory of operation, and then presents some of the more recent successes in mobile truck mounted, and stationary applications. While examining the benefits of using Coriolis meters in these propane measurement applications, we will review notable practical lessons learned. The use of mass flow devices in the LP gas industry provides undeniable benefits. With simple precautions of use, propane suppliers can now enjoy this accurate, reliable, and virtually maintenance free technology.

### **Introduction**

The mathematician Gustave De Coriolis first described the Coriolis Effect, which is an inertial force experienced by a moving body (or liquid) in a rotating coordinate system. A Coriolis force flowmeter measures the effect of this force acting on a fluid flowing in a vibrating tube. Generally, Coriolis meters use a pair of tubes vibrating in a sinusoidal pattern with respect to one another. The tubes, along with their accompanying drive coil and sensor coils, form the transducer for the measurement system. A flow computer, either integral to the unit or housed separately, processes raw signals from the transducer. The two form a proprietary system whose components are not interchangeable with those from another manufacturer.

Coriolis mass flow measurement devices detect the actual mass, rather than the volume, of the substance passing through the meter. Initially developed as a laboratory instrument, Coriolis meter patents date back to the early 1970s. The first viable commercial meter was introduced in 1978. Since then, the market has expanded rapidly, and mass flow is the fastest growing flowmeter technology, replacing positive displacement meters in applications in the chemical, food, and pharmaceutical sectors.

Coriolis meters exhibit greater range and accuracy than traditional positive displacement devices. They can measure fluid mass flow rates from 0.04 pounds per minute to 25,000 pounds per minute, with accuracy better than 0.1 percent and with measurement repeatability of less than 0.1 percent.

Mass is a primary measurement and remains constant. Since mass flow meters measure mass directly, the result is independent of the physical properties of the fluid such as viscosity, temperature, pressure, or density. Volume changes with temperature, and volume measurements must be corrected based on ambient conditions. For example, 362 pounds of alcohol occupy 55 gallons at 41<sup>o</sup>F, but at 77<sup>o</sup>F, the same mass occupies 56 gallons.

Coriolis meters exhibit metrological performance unmatched by volumetric flowmeters, with increased accuracy, improved product consistency and reduced maintenance. Precision measurement of continuous processes over long periods reduces raw material consumption and inventory shrinkage. This performance, along with the Coriolis meter's suitability for a wide variety of fluids and applications, fueled the success of this technology. Although initially more expensive, the meters quickly earn back the investment.

### **Theory of Operation**

A Coriolis flowmeter measures the force acting on a fluid flowing within an oscillating tube. Although it is possible to accomplish a Coriolis measurement using a continuously rotating device or an oscillating single tube, the most familiar Coriolis meter designs typically use a pair of tubes that are vibrated out of phase. The use of two tubes results in a relative displacement measurement, which helps to minimize any adverse effects of environmental vibration. A number of tube geometries are possible – helical, U-shaped, S-shaped, and others. The following example will describe the operation of a device formed from a pair of Omega-shaped tubes.

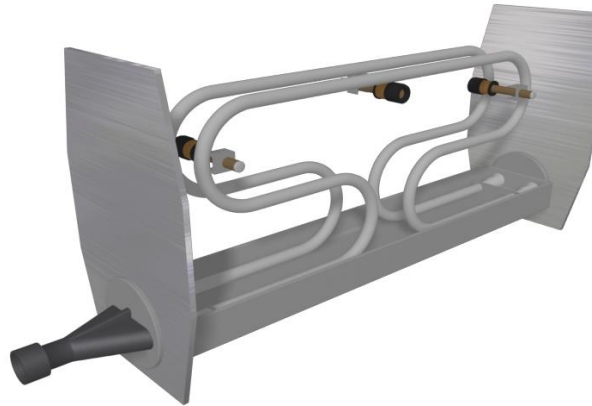


Fig. 1. Dual Omega-Tube Coriolis Meter

The tubes are vibrated in a reciprocating pattern, driven by an intrinsically safe magnet and coil assembly (a solenoid) attached to their midpoints. The solenoid drives the tubes at their resonant frequency, causing them to vibrate in and out in opposite directions. The inlet and outlet of the tube is held fixed as the tube vibrates in an arc about this axis. Two more coil and magnet assemblies, one at each end of the assembly, serve as sensors, generating a sinusoidal voltage proportional to the relative position of the two tubes. The output signals of these coils are equal in frequency and amplitude, and in phase when there is no flow through the tubes.

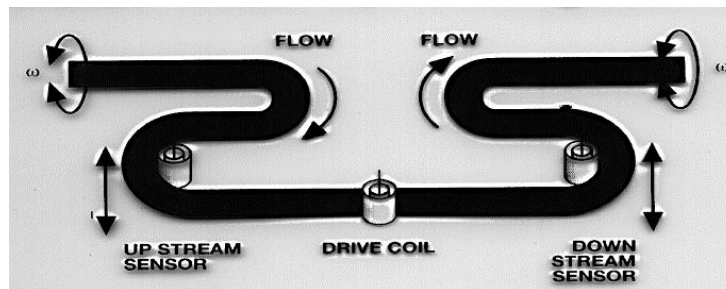


Fig. 2. Drive Coil and Sensors

When fluid flows in the moving vibrating tubes, Coriolis forces are created. When fluid flows in the tube it initially flows away from the axis as it approaches the midpoint of the tube. Once past the midpoint, the same amount of fluid returns toward the axis. At any time the mass of fluid at either end of the tube has an equal and opposite Coriolis acceleration and hence exerts an equal and opposite force  $F$  equivalent to  $2mV\omega$  on the tube which tends to twist it. The difference between the positions of the two sensor coils due to the twist of the tube produces a difference in phase between the sinusoidal voltages. This phase shift is directly proportional to the mass flow rate of the fluid flowing through the tubes, and is the basis of the Coriolis flowmeter principle.

CORIOLIS FORCE,  $F = 2 m V \omega$

$m$  = MASS OF FLUID  
 $V$  = FLUID VELOCITY  
 $\omega$  = RESONANT FREQUENCY

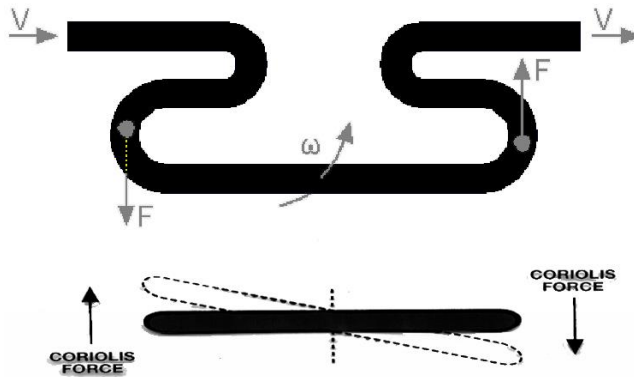


Fig. 3. Coriolis Force Calculation

### Accuracy and Zeroing

Under no-flow conditions the fluid exerts zero Coriolis force on the tubes and no twist is seen. No twist means no relative positional difference between the coils and the sinusoidal voltages are in phase. Zero phase difference means zero mass flow rate. This is called the zero of the meter. However, manufacturing tolerances will introduce a slight phase difference at no-flow. This is known as the zero error or zero shift. There are also small fluctuations in the phase difference associated with installation variations and the processing of the sensor signals. The combination of these factors is known as the zero stability.

Coriolis meter accuracy is stated as percentage of mass flow rate plus or minus the zero stability. The zero shift error becomes the dominant portion of the overall accuracy at the lower end of the flow range. Alternatively, the accuracy may be stated as a percentage of rate for flow rates above some low flow threshold and as a percentage of flow range for flow rates below the threshold.

It is important to remember that the zero stability or zero shift error, is a constant error regardless of flow rate. When a new meter is put into service, it undergoes a process called “zeroing”, during which this error is calculated so that it may be removed from all subsequent calculations.

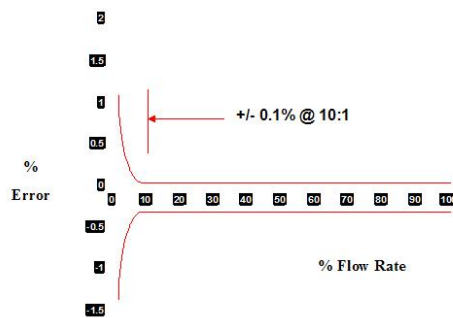


Fig. 4. Mass Flowmeter Accuracy Curve

### Density and Inferred Measurements

Coriolis meters can also be used as densitometers. The tubes can be viewed as a spring and mass assembly. Once placed into motion, a spring and mass assembly will vibrate at its resonant frequency. The Coriolis meter is also vibrated at its natural “harmonic” frequency. The relationship between density and the vibration frequency and period can be quantified. As

the density of the fluid inside the tubes changes, the frequency of vibration will also change. This frequency measurement is inversely proportional to the density.

$$\rho \propto 1/f_n$$

Additionally, a temperature probe is mounted on one of the flow tubes. Temperature changes the stiffness of the tube; therefore, it affects the density calculation. The flow computer compensates for this change in the tube's elasticity.

A number of other measurements can be inferred from the basic measurement of mass and density. These include volume flow rate, percent concentration of mixtures and solutions, percent solids of slurries, Brix (a measure of sugar concentration), degrees API, and degrees Baume (both related to specific gravity).

### Certification, Calibration, and Proving

A new Coriolis meter is calibrated at the factory against a traceable weigh scale to establish a calibration factor for the transducer. Recalibration is not necessary on start up under field conditions; however, periodic verification or proving is advised to confirm the accuracy of the instrument during its operating life.

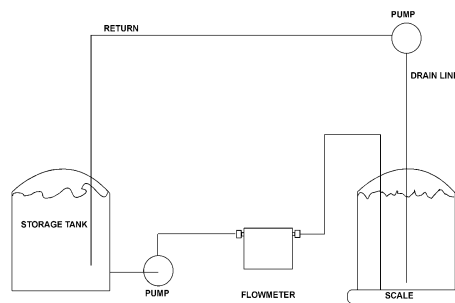


Fig. 5. Calibration Setup with Scale

There are two common proving methods -- using a mass standard or a volumetric standard. If the meter is indicating mass and is proven against a mass standard, the liquid properties during the proving run are not important to the calibration.

When proving a Coriolis meter indicating volume against a volumetric pipe prover or master meter, steady state conditions between the meter and prover are necessary to minimize variations in liquid density. A pipe prover consists of a cylinder of known volume fitted with a piston. As the collected calibration fluid displaces the piston, the meter sends pulses that represent the total volume. The meter and prover volumes can be compared and, if necessary, corrected back to a common reference condition.

As mentioned before, it is essential to maintain steady state conditions between meter and prover to minimize liquid density changes. A continuous density reading is required for the volume-to-mass conversion because changes in the physical properties of the fluid during the proving run introduce errors. Temperature, pressure and variation in entrained air content can cause density to change.

Combining instrument readings always results in a greater cumulative error and more uncertainty of the final proving result. Sufficient product should be collected to allow the resolution of the proving element to match the desired resolution of the meter calibration. API Standards are available to set out the recommended procedures for verification of Coriolis flowmeters.

### Meter Selection

Given the wide turn down (100:1) of a typical Coriolis meter, several meter sizes may be acceptable for a given flowrate. The user selects a meter to match the optimum performance in the application. Pressure drop and accuracy are evaluated to optimize the meter size and cost effectiveness.

The vapor pressure of the fluid should be taken into consideration to prevent cavitation inside the meter. Cavitation reduces both measurement accuracy and meter life. Manufacturers offer sizing programs to aid selection, which calculate pressure drop across the meter, predict accuracy under the prevailing operating conditions and any back pressure required to prevent cavitation.

Materials of construction, as for any meter, are a crucial part of the selection process to ensure long life. Coriolis meter flow tubes are smaller and thinner than the process piping and corrosion by chemical attack can cause further wall thinning.

Abrasive fluids at high flow velocities have resulted in tube failure. Manufacturers publish material compatibility guides and instruments in various materials to suit the range of process requirements.

### **Installation**

The advantages of accuracy, stability of calibration and lack of maintenance so far discussed depend on correct installation of the meter.

#### Mounting

Best performance of Coriolis meters can be obtained with rigid pipe supports at either end as close to the inlet and outlet connection as possible. The supports isolate pipe vibration, which, if near the flow tube natural frequency, can superimpose on the tube vibration and cause errors. The meter casing should not be directly supported.

Figure 6 shows a correct mounting of a mass flowmeter transducer.

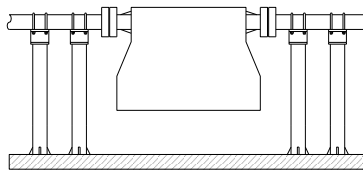


Fig. 6. Mounting a Mass Flowmeter Transducer

Often times, a spool piece equal in length to the transducer can be employed to align pipework during construction. Excessive bending, compression or torsion on the flanges can result in a change in the zero drift during service. The spool piece should remain in place through initial pump startup so that any remaining piping debris is not pumped into the meter.

Normally, straight piping runs are not required before or after the meter to maintain accuracy; however, it is recommended to use straight pipe up stream and downstream to support the transducer. A shut-off valve should be included downstream to prevent flow during zeroing of the meter. If possible, zeroing should be done with the pump running. For continuous operations a bypass line should be provided around the meter.

#### Orientation

Meters should be orientated to allow the tubes to be constantly filled with fluid and avoid the settlement of suspended solids or collection of gas. Vertical or “flag orientation”, with flow upward, prevents air entrapment in the meter tubes and is self-draining for some tube geometries. In a horizontal mounting, tubes should be positioned below the pipe to prevent air collection. Product coating the wall dampens tube vibration; flow velocity and temperature conditions should be maintained to prevent this settlement in the meter during operation.

#### Entrained Gas

Entrained gas above roughly five percent by volume will often result in poor performance. The gas void tends to dampen tube vibration. System design should remove the possibility of gas passing through the meter in liquid applications. An air release mechanism up stream of the meter may be required. Additionally, in volatile fluid applications, sufficient backpressure should be maintained to prevent flashing of the fluid to vapor.

#### Vibration

Pumps are a major source of vibration and meters should be isolated from them by distance or mechanical means such as resilient couplings or pulsation dampers. Zeroing the meter with the pump running will be of benefit here. Multiple flow sensors in close proximity can transmit vibration to each other. Care should be taken to provide each sensor with separate support.

## Truck-Mounted Installation of Coriolis Flowmeters for Retail LPG Delivery

Although the last decade has seen rapid adoption of electronic registration devices for tank trucks in custody transfer applications, mechanical volumetric meters are still used in a majority of the new systems. In these systems, the meter's gear train is used to turn an encoder that generates the signal supplied to the electronic register. While electronic registration greatly improves the efficiency of a metering process, the system is still subject to the accuracy and maintenance constraints of the mechanical meter. In 2004, the first mass flowmeter was approved for mobile LP gas custody transfer. This fully electronic system yields reduced product losses, low maintenance, and faster deliveries.

When used on a tank truck, the meter is part of a system that includes a vapor release, differential valve, and electronic register. The system is mounted in a similar position to a traditional volumetric meter at the rear of the truck. The meter is connected in-line to the vapor release and differential valve via 2" flanges rated at 300 lbs pressure. One way of mounting a mass flowmeter on bobtails is shown in Figure 7. In this configuration, the meter is rigidly positioned for effective performance.

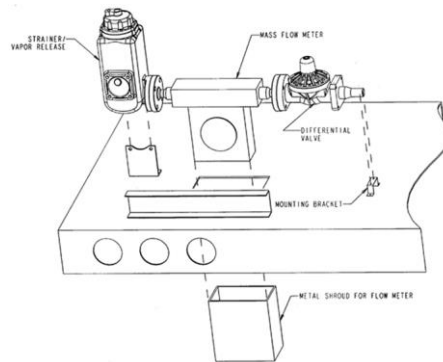


Fig. 7. Mounting Meter through Truck Deck

The advantages of accuracy, stability of calibration and lack of maintenance depend on correct installation of the meter. A specially designed bracket and flexible hoses reduce vibration and mechanical stresses. Electrical connections should be made securely and the system should be properly grounded to eliminate any electromagnetic and RF interference.



Fig. 8. Flexible Hoses used at Inlet and Outlet

Early units were mounted vertically to prevent unnecessary stress on the tubes when turned sideways, and required that a hole be cut into the deck of the truck to accommodate the height of the meter within the exiting piping profile. Newer units with improved resistance to the shock of moving over rugged terrain have now been mounted horizontally with good success and without cutting the truck deck.

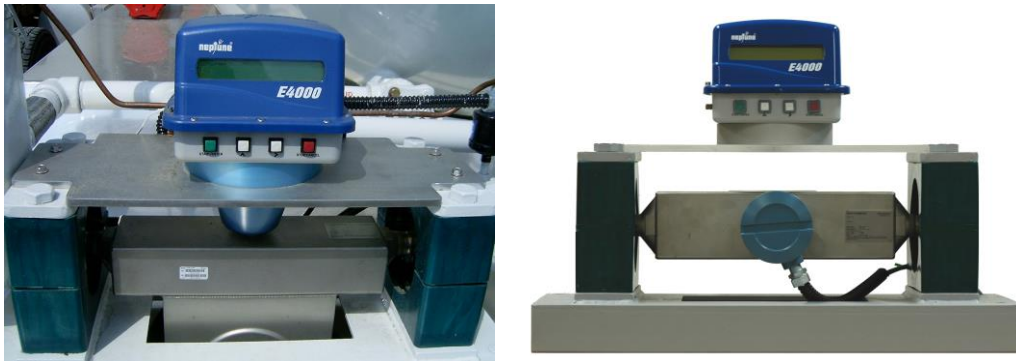


Fig. 9. Vertical and Horizontal Mounting Methods

### **Benefits of Coriolis Flowmeters for Mobile Delivery**

#### Reduced Loss

Because the mass flowmeter has no moving parts to wear, its accuracy should not degrade over time. Typically, the mass flowmeter may be 0.5% more accurate than a mechanical positive displacement meter. If a retailer sells 500,000 gallons per year from one bobtail, this equates to loss reduction of 2,500 gallons. At \$1 per gallon cost, the dealer recovers \$2,500 per year just from gas loss reduction on one bobtail. Selling the 2500 recouped gallons at an average margin of 50 cents per gallon results in another \$1250 per year in gross margin. In this case the incremental revenue may be more than \$3,750.

#### Reduced Repair and Calibration Costs

Since there are no moving parts in the mass flow meter, there is no need to replace worn parts, saving replacement part costs and reducing down time for the drivers. Accuracy tolerances have been seen to hold over time, but if there is a need for calibration, the process is a simple change on the keypad of the electronic register, subject to local approval. There are no gears to change or multiple calibrations needed, again reducing down time.

### **Coriolis Flowmeters in LPG Bulk Plant Inventory Management**

Coriolis meters are used in bulk plant facilities to monitor bulk offloading, bulk loading, and container filling. To provide precision control from receiving through distribution, Coriolis technology serves as an integrated part of a control package for an entire bulk distribution operation. The bulk inventory tracking system brings all product flows under measurement and control. Coriolis mass flowmeters measure every liquid-phase flow and vapor return loop and relay the data to a central monitoring computer. Custom software provides a detailed log of every event, and can be interfaced with accounting software or monitored remotely to track the status of every process in the plant. The result is reduced shrinkage, more efficient ordering and billing, and optimized cash flow. Additionally, the mass flowmeter's density measurement capability enables the user to ensure the purity of product being delivered.

#### Maintaining Liquid Filling Systems in Volatile Environments

Managing inventories in the LPG industry entails a broader set of challenges that are not present in the measurement of other liquids. The volatility of LPG requires tighter controls to ensure that the product remains in one of its pure states: liquid or gas (vapor). There is not a particular type of flowmeter that can measure all types of fluids under all conditions; more specifically, the accuracy and in some cases the ability to measure fluids in a mixed state of liquid and gas is significantly hampered if the percentage of either state is less than 95% by volume. Positive displacement flowmeters can be designed to measure "liquids only" or "gasses only". Coriolis mass flowmeters are able to measure liquids and gases accurately, without the need of re-calibration, as long as the percentage of the minority state of the fluid (e.g., vapor in the measurement of liquids) is kept under 5%.

For optimal measurement accuracy, it is necessary to maintain LPG in its liquid state. In the past, typical transport unloading operations included mechanical systems of tanks, floats, and valves to separate the vapor from the liquid. However, these systems had several major drawbacks:

- 1) The vapor eliminator sends the vapor directly to the storage tanks, by-passing the meter; therefore, this vapor is not accounted for in the measurement process.
- 2) Structural properties of the vapor eliminator, piping, and flow profiles create a drop in the line pressure between the vapor eliminator and the flowmeter. This pressure drop causes the product to “flash” into its vapor state, causing a two-state flow condition in the flowmeter.
- 3) High cost.

**Dynamic Vapor Exclusion**

To prevent vapor from entering the flowmeter, a process called Dynamic Vapor Exclusion (DVE) has been developed. The DVE systems minimize the amount of vapor entering the liquid meter by maintaining enough pressure in the flow line to keep the product in liquid form. This is accomplished using an inexpensive, yet efficient combination of: control valve, backpressure or differential pressure valve, and a mass flowmeter with the capability of measuring density and communicating this measurement.

Figure 10 illustrates the preferred configuration of the DVE. Figure 11 shows an alternate configuration in which a Differential Pressure Switch and a Solenoid Valve replace the Backpressure valve. Figure 12 shows a more economical configuration; however, it requires a vapor return operation in order to implement the differential pressure control.

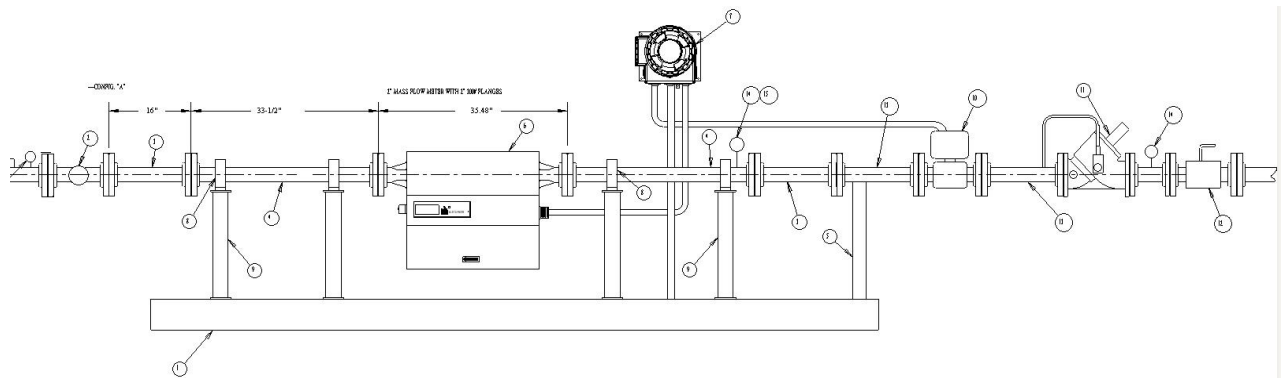


Fig. 10. Preferred DVE Configuration

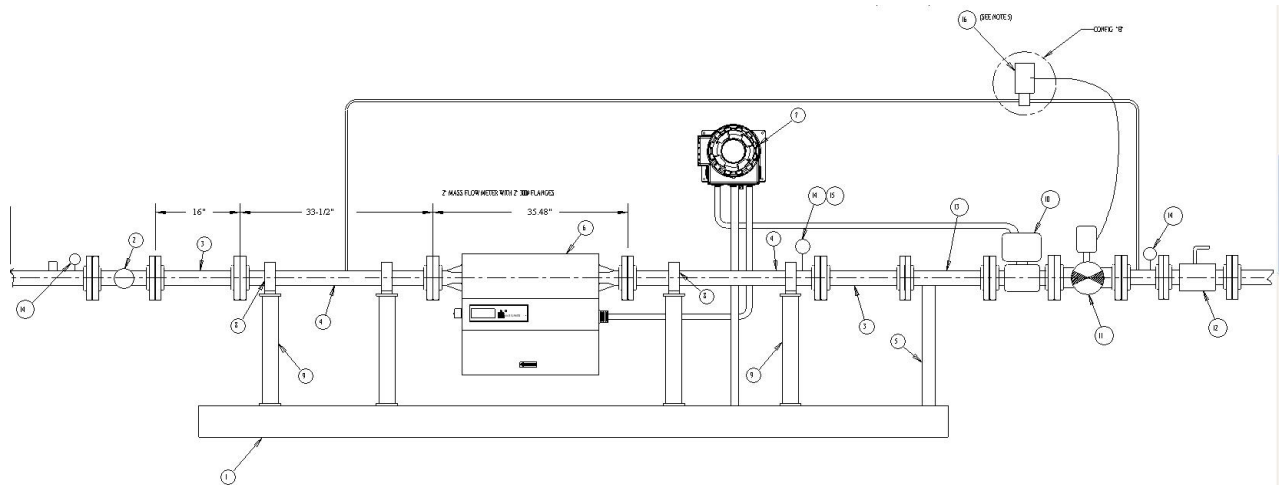


Fig. 11. Alternate DVE Configuration



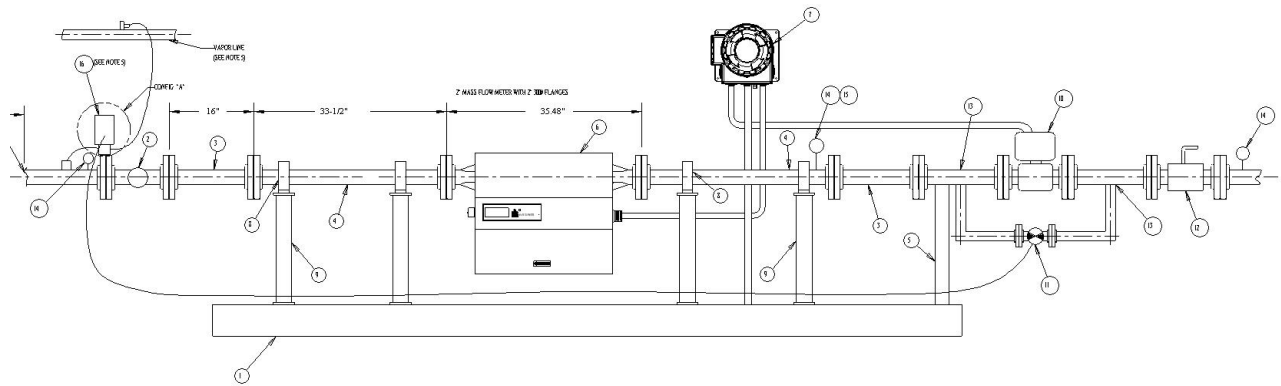


Fig. 12. Lower Cost DVE Configuration

The settings explained above will maintain the line packed with product in the liquid state most of the time. However, there might be situations in which large amounts of vapor will be present in the liquid line. These situations include:

1. “Empty-to-empty” deliveries. The liquid line starts empty (dry) and ends empty because the transport is unloaded until no more liquid (only vapor) flows out of it.
2. Deliveries of “high-vapor-pressure” products (such as pure propane) under high temperature conditions.

In a “worst-case-scenario”, where vapor will be present in the liquid line, the DVE will optimize the operation the following way:

1. After the transport truck is connected, the compressor (or pump) starts and the manual valves are opened; the Backpressure valve holds the line close until the pressure builds to a pre-set that exceeds the vapor pressure of the measured product. This will cause most of the product (in vapor state) to condense into the liquid state.
2. When the Backpressure valve opens, the pressure in the line drops. This might cause high-vapor-pressure products to flash; the bubbles formed will cause the measured density of the product to drop. At this point the mass flowmeter sends a low-density signal to the control valve, causing it to go to its “almost-closed” condition. This increases the pressure in the line, which in turn causes the vapor to condense to the liquid state.
3. From this point on, the mass flowmeter adjusts the control valve to provide for the optimum flow setting that will provide the maximum flow allowable with enough backpressure to keep the product in the liquid state.

At the end of the delivery, when there is not enough pressure in the line the Backpressure valve closes and remains closed until the next delivery.

### Vapor Measurement in Inventory Balance

The goal of effective Inventory Balance Management is to account for the total quantity of product in the plant’s storage tanks at all times. Therefore, measuring all of the product that enters and that leaves the storage tanks in either gas or liquid phase should be part of this goal. The high volatility of LPG is a factor that can complicate the measurement process; understanding and accounting for this characteristic is the key to complete and accurate measurement. Measuring the flow of the vapor phase in the management of inventory balance is almost as critical as the measurement of the liquid phase when an accurate inventory is the goal.

### Pumping Liquids

When pumps are used to unloading transport or load delivery trucks, it is necessary to provide a path for the vapor to circulate from one container to the other. This prevents the pressure in the receiving tank from becoming too high and slowing down or prematurely ending the filling process. This flow of vapor is movement of product that adds or subtracts to the inventory; therefore, to ensure that all product transfer is accounted for, it is important to measure it and report the measurement as part of the inventory operation.

### Injecting Vapor to Retrieve Liquid

LPG transports may also be unloaded by using compressors to inject vapor into the transport's tank, increasing the pressure in order to push the liquid into the plant's storage tanks. This flow of vapor reduces the plant's inventory and needs to be recorded. Some of the injected vapor changes into the liquid phase when the pressure in the vessel exceeds the product's vapor pressure. This liquid goes back to the plant's storage tanks and is accounted for by the meter that measures the liquid phase. However, many transfer measurement processes occur at temperatures that cause the vapor pressure to be high enough to keep over 50% of the injected product in vapor form. In this case, without a meter measuring the injected vapor, the transport truck would leave the plant, taking with it hundreds of pounds of vapor that were not accounted for in the inventory balance process.

### Recovering Vapor

To make the unloading of product into the plant more efficient, some transport unloading operations incorporate a "Vapor Recovery Cycle". The object of this measurement cycle is to recover most of the vapor that was injected into the transport's tank that did not condense (under pressure) into the liquid phase. This product is returned to the storage tanks and should be accounted for as an increase in the inventory total. As with the previous cases, it is important to measure the flow of the vapor to account for the net product entering and leaving the inventory.

### Equivalent Liquid Volume

There is no more accurate way to manage bulk plant inventories than by means of "Mass Inventory Management", i.e., accounting for product transfer in units of mass (pounds, kilograms, etc.). Inventory by mass instead of volume precludes dealing with volume changes due to temperature and/or pressure. Nevertheless, many customers still like to have the measurement results in familiar volumetric units. For this purpose, the system provides volume units as well as mass.

The volume of a liquid in a container is easily quantifiable by metering; however, the total volume of a gas in a container is always the volume of the container, regardless of the amount (mass) of gas in the container. A mass flowmeter calculates volume by dividing the mass measured by the density measured. The density of gas is very small compared to the density of liquids and solids. Therefore, dividing the mass of a gas by its density yields very large volume values. These large volumes of vapor, without associated pressure ratings, cannot be quantified into an inventory balance system without the addition of expensive electronic manometers and tables that require knowledge of the exact composition of the product. In order to quantify the amount of vapor transfer into a tank in volumetric units, a method of defining the amount as "Equivalent Liquid Volume" has been developed. By using a measurement system with one flowmeter to measure the liquid phase of the product flowing into the storage tanks and another flowmeter to measure the vapor phase injected into the transport's tank, we can determine the mass of the product in the vapor state and divide it by density of the product in liquid state, to infer the equivalent liquid volume of the vapor. This equivalent volume can be easily added or subtracted to the total volume of the liquid measurement to account for the complete inventory balance in volumetric units.

### **Conclusion**

Coriolis technology has proven cost effective for many applications. With better understanding of the technological constraints, we have learned how to deploy Coriolis mass flowmeters into both mobile truck mounted and stationary applications (both vapor and liquid) in LPG bulk inventory and transport applications. These advances bring improved efficiency and reduced product losses to the LPG distribution and sales business.