CHAPTER 1
INTRODUCTION

1.1 Background

Metering technology offers a number of possible options for the measurement of compressible natural gas (CNG). However, because of the rapid variation in pressure, temperature, gas density and flow during a fill, and the potential for variation in gas composition over time or by location, some technologies are more appropriate than others. Technologies available for measuring CNG could be divided into four types: momentum flowmeter, volumetric flowmeter, pressure-volume-temperature (PVT) method and mass flowmeter [1], [2].

Examples of momentum flowmeter are orifice plate meters, venturi meters, sonic nozzles, etc which all involve sensing the momentum of the flowing gas. However calculation of the flow rate from the gas velocity also requires knowledge or measurement of the gas density. These meters have limited range and usually multiple meters might be required to cover a given range of measurements and are subject to pulsation effects, and hence unsuitable for the rapidly changing flow regime inside CNG dispenser. Momentum flowmeters are commonly used for relatively steady-state metering applications such as industrial process control [1], [2], [3], [4].

Examples of positive displacement flowmeter are turbine and the ultrasonic flowmeters. Both flowmeter techniques offer reasonable performance and low cost. Turbine flowmeters are velocity measurement devices in which, a uniform flow profile with straight piping upstream and downstream is required to measure the flowing gas. By knowing the rotational speed of the turbine blade and pipe diameter, a volumetric flowrate could be calculated [1], [2], [3], [5], [6].

The volumetric flow can be converted to a mass flow if gas properties are known. However, inaccuracy could develop due to variations in gas composition and pressure affecting the molecular weight and density of the gas measured. In addition, these meters are unable to follow sudden changes in flow rate due to changed of inertia and momentum in the turbine both for the case of increasing as well as under decreasing flow. This gives rise to a “lag” in measurements during rapid changes of flow rate. Furthermore, as the meter consists of moving parts, regular calibration is required to allow for drift in the meter due to mechanical deterioration.

Ultrasonic meter operates by measuring the time difference between ultrasound pulses, traveling diagonally across the path of the flowing gas, with and against the direction of gas flow. This requires extremely accurate time measurement, down to nanosecond levels. Irregularities in the flow pattern within the pipe can cause errors and several “flight paths” are normally used across the pipe to provide an average measurement. The response time to changes in flow rate is relatively slow. Ultrasonic meters are commonly used for domestic gas supply at low pressure. For large, high pressure gas pipelines; no manufacturer currently produces small, high pressure meter of this type suitable for CNG applications [1], [2].

PVT metering is a mathematical method which uses measurements of temperature and pressure to calculate the amount of gas in the on-board storage from the known cylinder volume. However, the accuracy of this method is determined by a number of factors i.e., non-ideal behavior of gases, effect of gas composition, change of compressibility factor, z, with pressure and heating effect as pressure rises inside the cylinder. As the CNG fill proceeds, compression of gas into the cylinder would cause the in-cylinder temperature to rise. The temperature rise is dependent on factors such as initial pressure of the gas and the fill rate. A low flow rate would allow the heat generated to dissipate through the cylinder walls. Ideally, temperature should be measured inside the CNG cylinder. PVT method could be designed by developing programmed algorithms to allow for the above factors [7], [8], [9], [10], [13].

However, the use of an “average” gas composition and density, together with errors in the measurement of temperature and pressure could still cause inaccuracy. One of the interesting works of PVT meters for CNG metering application is found in Radhakrishnan *et al.* [13].

Examples of mass flowmeters are thermal mass flowmeters and the coriolis mass flowmeters. Thermal mass flowmeters rely on heat transfer within the flowing gas being measured. This is dependent on the heat capacity of the gas, which must be known. For gas mixtures the value is dependent on the gas composition, hence changes in composition will introduce inaccuracy. Heat capacity is also dependent to a lesser extent on gas pressure and temperature. Because the meter relies on measurement of temperature difference between two thermocouples, the response to step changes in flow is relatively slow. Due to this, the meters are not widely used in CNG applications. Further discussion on other types of mass flowmeter i.e., coriolis flowmeter would be found in the next section [12], [13], [14], [15].

Any flowmeter designs developed for CNG should comply with international standards i.e., ANGVA, ENGVA and IANGV standards. Whilst, the maximum permissible errors for flowmeter patent and complete dispenser system are $\pm 1\%$ and $\pm 1.5\%$, respectively. For subsequent verifications, the maximum permissible error is $\pm 2\%$ [1], [2], [16], [17], [18].

1.2 Problem Statement

Sales and purchases of gas involve significant flow of money across the industry; hence even a slight error will cause a loss of million either to the seller or purchaser. A number of gases metering technologies are available in the market offering a relatively accurate measurement of CNG i.e., vortex, orifice, turbine, thermal and etcetera. However, the accuracy of these measurements depends on various dynamic factors and fluid parameters such as rapid variation in pressure, temperature, gas density and gas composition over time or by location.

Unlike liquid, volume of gas is affected by temperature and pressure as the ideal gas law stated that the higher the temperature, or the lower the pressure, the greater the volume of the gas would be. Therefore, to avoid flow measurement from such dynamic errors, a new technique or novel concept of flowmeter is required for the measurement of CNG. One of the options is to use natural force phenomenon that could be derived from fundamental physics, a force known as coriolis. Coriolis flowmeters are used almost exclusively by CNG dispenser manufacturers throughout the world to meet the higher standard and specification of metering CNG [19].

The use of coriolis flowmeter in CNG refueling system has been:

- to demonstrate the cost savings of CNG
- for testing of new and advanced parts of CNG kits
- for documentation when paying state taxes on CNG sold
- for billing and accounting purposes when CNG is sold to another party
- to help monitor maintenance requirements before major maintenance is required; and
- to automate dispenser systems and for control of cascade sequencing

The above applications indicate the importance of having a new technology for coriolis flowmeter that could provide very accurate measurement of the CNG. The critically of the measurements is when there is a requirement to have an alternative to the coriolis, whether as a verification of the values provided by the coriolis, or if when the coriolis fails, or even to measure a medium of pressure excessively high for a coriolis.

1.3 Motivation

Coriolis is becoming widely used in flow measurement of compressible gas flow and, in fact many manufactures have patented their own coriolis flowmeter; see for example Micro Motion Inc [20], Krohne Ltd [21] and Endress Hauser [22]. Generally, the basic architecture of each coriolis flowmeter is very similar. It relies on the measurement of certain vibrational characteristics of a tube through which gas flows. The vibrations are dependent on the mass flowrate of gas in the tube and hence it provides a true mass measurement [15]. In addition, the natural frequency of the tube could be used to measure gas density which could also be used to calculate volumetric flow. The design of the flowmeter is such that no obstruction is placed into the gas flow path hence, it is able to respond to rapid change. This is different than for example an orifice plate flowmeter which could not accurately measure flow at low pressure [1]. Since it is a mass flowmeter, which is unaffected by gas composition or pressure, coriolis has been chosen as the technology for the measurement of CNG. Majority of CNG manufacturers would use coriolis flowmeter if metered dispensation of gas is required. Currently, there is no method (other than using the less accurate meters like the turbine and vortex) being implemented as an alternative to a coriolis meter to be used as a flowmeter., in case the coriolis would fail to function properly such as hydrogen metering [23], wet gas metering [24], or multiphase metering [25]. Hence a technique to obtain a mass flowrate measurement of the flow medium ‘indirectly’ or ‘meterlessly’ by monitoring the pressure exerted by the mass of the gas in the supply and receiver tanks is required. Given the scenario above, the motivation behind the research is not to develop a vibrational tubes coriolis flowmeter, but to develop an algorithm that would perform as a coriolis in an embedded controller to be known as inferential coriolis. By embedding it on a controller, the method would not only have the same function as current coriolis flowmeter but would encompass several advantages expected including:

- simple mathematical form
- conveniently programmed to computer codes
- reduced production cost
- benefits to oil and gas industry

In doing so, the major challenge is to develop suitable algorithm for coriolis i.e., a mathematical model that would measure mass and mass flowrate of CNG with maximum permissible error. To define such system, an experimental approach is used throughout the research i.e., an approach known as System Identification (SYSID) theory [26], [27], [28], [29], [30] and [31].

1.4 Objectives and contribution of the research

The particular work conducted has been the identification and formulation of the algorithm for mathematical model of the inferential coriolis, and simulate, verify, and validate its functionality on a test rig. The primary emphasis of the work is placed on evaluating the suitable SYSID to use, where different methods have been compared. The chosen method has been considered based on its ability to imitate the real behavior and accommodate the various demand variations. Several tests with different switching patterns at the source have been studied.

The research methodology includes;

- Introducing an approach for mass flowrate measurement of coriolis using SYSID theory by considering the coriolis flowmeter as a gray-box model.

- Developing a simulation model using MATLAB to represent a coriolis measuring system which is used as a tool for re-evaluating and re-designing the algorithm.

- Designing the coriolis algorithm development using LabVIEW to measure mass flowrate, and embed it on FieldPoint controller for actual testing on an experimental rig.

- Investigating the effectiveness of the coriolis measuring algorithm using various possible cases/scenarios.

The contributions of the research are to;

- **Propose a mass flowrate measuring algorithm, referred to as 'inferential coriolis'.** The unique feature of this measuring algorithm is its similar function to the coriolis flowmeter developed by relating the coriolis flowmeter to its mathematical model based on SYSID method.

- **Present an approach for the development of an inferential coriolis with parametric estimation models using SYSID.** The development involves: the mathematical model of the coriolis flowmeter, the data collection of an actual coriolis measurement, and the parametric models analysis and design.

- **Investigate the effectiveness of several parametric estimation models of the coriolis.** As variables such as the order and coefficients of the parametric models have significant effect on the performance of the inferential coriolis developed, a number of SYSID methodologies are investigated. The measurement of the inferential coriolis to the different SYSID models is confirmed through detailed quantitative analysis.

- **Build and implement an inferential coriolis meter.** It is important to achieve a measurement within the maximum permissible error. Implementing the coriolis measuring algorithm on an experimental rig with the set-up resembles the actual CNG filling station using an actual coriolis flowmeter enables the verification and validation of the particular SYSID model.

1.5 Outline of the thesis

This thesis is divided into two parts. In part I, consisting of chapters 1 and 2, an introduction is given to gas metering technologies available for the measurement of compressible natural gas (CNG) with highlights on the importance of the approach used in the research work. A review on the analysis of the problem is made with the intend of setting the scope for the research work. Part II, consisting of chapters 3 to 5, presents the approach of developing model using SYSID theory for the flow measurement of CNG and the model in experimental test rig, including the model analysis and design, model verification and validation, performance analysis, and the experimental design and the illustrations with some application examples. The detail outline of the thesis is as follows:

Following the introduction in Chapter 1, Chapter 2 focuses the research to a selection of literature reviews to provide a view of what are the research works regarding CNG flowmeter technologies which covers momentum flowmeter; volumetric flowmeter; pressure-volume-temperature (PVT) based flowmeter and mass flowmeter.

Chapter 3 concentrates on theory of SYSID to identify coriolis mass flowrate (CMF) transfer function algorithm. The important point is to describe theoretical development of SYSID i.e., mathematical theory, parametric structure, statistical order, parameter estimation method and validation of models.

Chapter 4 discusses methodology of SYSID to develop algorithm for inferential coriolis that has been embedded in the FieldPoint controller and tested on experimental test rig.

Chapter 5 explains on results of experiments to analyze performance of the proposed inferential coriolis which could be summarized into three areas: single pressure flow; continuous pressure flow; multi pressure flow with disturbances.

Finally, Chapter 6 gives the conclusion of this thesis and suggests some examples i.e., hydrogen refueling, wet gas measurement and multiphase flowmeter to illustrate the application of inferential coriolis in evaluating the effectiveness of the develop method.