# MODELLING PRESSURE REGULATORS USING OPERATIONAL DATA

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*Abstract*

Pressure regulators are the most important components of gas distribution networks. Operational optimization and failure-mode analyses of these networks require simple and reliable models for pressure regulators. Using dynamic operational data, a novel approach to model a pressure regulator is presented. A pressure regulator is modelled as a virtual feedback control system, with a control valve and a proportional controller along with measurement lag. The control loop parameters, representative of the pressure regulator, are determined using a set of dynamic operational data. The estimated parameters can then be used to predict the performance of the pressure regulator under varying scenarios. The proposed modelling approach is applied on an example pressure regulator. The transient response of the gas regulator is predicted quite well. Overall, this study provides a simple method of predicting the performance of pressure regulators with reasonable accuracy.

*Keywords*

Pressure regulators, gas distribution, transient response, natural gas.

## Introduction

The distribution of gas from local/regional supply points to the consumers requires reduction and control of pressure progressively in several steps along the distribution lines, performed by multiple stages of pressure regulators. Pressure regulators are generally designed to maintain stable pressure levels at steady conditions. However, in practice, the operation of a gas distribution system is highly dynamic, and may involve several instabilities such as metering perturbations, oscillating pressures with high amplitudes, etc. (Rami et al., 2007) Furthermore, there are very few predictive warning systems that can indicate the probable failure of a pressure regulator, which can cause major supply disruptions. Therefore, it is important to develop predictive models for pressure regulators that benchmark operating characteristics to enable their continuous monitoring, fault-detection, and troubleshooting.

Pressure regulators must satisfy downstream demand while maintaining the outlet pressure within acceptable limits. An ideal regulator supplies downstream demand without any variation in the downstream pressure. However, the mechanical design of direct operated regulators always results in some deviation. The deviation in the regulated pressure due to varying downstream demand is called droop or offset. Direct operated regulators typically have higher droop while pilot operated regulators are designed to reduce droop significantly. In fact, pilot operated regulators can be treated as two direct operated regulators in series. (Emerson manual) Therefore, the modelling approach developed in this work for direct operated regulators can be easily extended to pilot operated regulators. Regardless of the type of gas pressure regulators, all regulators consist of:

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1) Measuring element
2) Loading element
3) Restricting element

The measuring element is usually a diaphragm, and its function is to sense the outlet pressure of the regulator in the form of a force, usually termed diaphragm force. The loading element is usually a pre-compressed spring. This generates a spring force that opposes the diaphragm force. The loading element allows the operator to preset the set point required for the outlet pressure. Lastly, the restricting element is usually a valve and plug combination, and is controlled by the interaction between the spring and diaphragm force. The restricting element physically and directly determines the valve opening, and hence the flow through the valve. If the spring force exceeds the diaphragm force, the net force acting results in the opening of the valve. This reduces the resistance for fluid flow, and hence allows greater flow through the regulator. Conversely, if the diaphragm force exceeds the spring force, the net force on the plug results in the closing of the valve. Only when the diaphragm force equals the spring force, the regulator is in equilibrium, and the outlet flow and pressure are steady. (Emerson manual)

Rami et al. experimentally studied the stability of a pilot controlled regulator. (Rami et al., 2011) Further, Rami et al. developed an analytical model to study the transient response of a pilot controlled gas regulator. (Rami et al., 2007) Though this first principles approach of modelling pressure regulators is rigorous, several non-realistic assumptions such as no increase in diaphragm area whilst in operation, simplified thermodynamic properties were made. Furthermore, this approach involves fairly complex system of partial differential equations. In contrast, Afshari et al. developed a dynamic model for direct operated pressure regulators using bondgraph simulation technique. (Afshari et al., 2010)

In this work, we present a novel approach of modelling pressure regulators as a feedback control loop. This approach is simple, reliable and can successfully predict the performance of pressure regulators.

## Pressure Regulator as a Feedback Control System

The idea behind this modelling approach is remarkably simple. The regulator diaphragm senses the outlet pressure with a certain time lag ($\tau_m$) , and compares with a set point pressure, preset by the spring. Based on this comparison, the regulator takes certain actions automatically to correct the error ($\varepsilon$) between the measured outlet pressure and the set pressure. Next, the regulator adjusts the valve opening to control the flow, which influences the outlet pressure.

This is very similar to a typical feedback control system, with diaphragm acting as the measuring element. illustrated in the following figure:

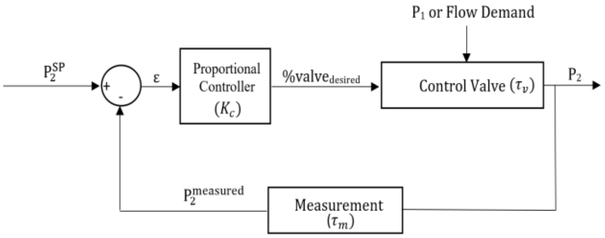

*Figure 1. Feedback Control System Block Diagram of a Direct Operated Gas Pressure Regulator*

where $P_1$ and $P_2$ are the inlet and outlet pressures, $P_2^{measured}$ is the outlet pressure sensed by the diaphragm, $P_2^{SP}$ is the set value of outlet pressure, $\%valve_{desired}$ is the desired valve opening, and ε is the error between the measured value and setpoint value of the controlled variable. The key parameters of the control loop that represent the operational characteristics of a pressure regulator are the measurement time constant ($\tau_m$), proportional constant of the controller ($K_c$), and the time constant of the control valve ($\tau_v$).

In general, a PID controller is represented by Eq. 1:

$$\mathrm{p(t)} = \mathrm{p_{ss}} + \mathrm{K_c}\left[\varepsilon(\mathrm{t}) + \frac{1}{\tau_\mathrm{I}}\int_0^\mathrm{t} \varepsilon(\mathrm{t})\mathrm{dt} + \tau_\mathrm{D}\frac{\mathrm{d}\varepsilon(\mathrm{t})}{\mathrm{dt}}\right] \tag{1}$$

The integral term utilizes the sum of historical errors to influence the correcting signal of the controller. The derivative term utilizes the current error gradient to predict what the future error will be, and hence influence the correcting signal. Being a mechanical system, there is no element of historical and predicted future error in a direct operated gas regulator. The diaphragm merely senses the current output pressure, and compares it with the set pressure. As such, only the current error term affects the correcting action by the regulator. Therefore, there should be no integral or derivative mode of control. Furthermore, the % valve opening is from the instantaneous position of the actuator. Therefore, we have:

$$\%\mathrm{valve_{desired}}(\mathrm{t}+\mathrm{h}) = \%\mathrm{valve_{actual}}(\mathrm{t}) + \mathrm{K_C}[\varepsilon(\mathrm{t})] \tag{2}$$

$$\varepsilon(\mathrm{t}) = \mathrm{P_2^{SP}} - \mathrm{P_2^{measured}}(\mathrm{t}) \tag{3}$$

$$\begin{aligned}\%\mathrm{valve_{desired}}(\mathrm{t}+\mathrm{h}) = \%\mathrm{valve}(\mathrm{t}) &+ \\ &\mathrm{K_C}[\mathrm{P_2^{SP}}(\mathrm{t}) - \mathrm{P_2^{measured}}(\mathrm{t})] \\ \text{with } \mathrm{h} \rightarrow 0 &\end{aligned} \tag{4}$$

The desired valve opening at the next instant of time would be a function of the current valve opening, and the current error.

The controller determines the desired opening of the control valve, and the control valve responds accordingly. In an ideal case, the actual valve opening should be equal to the desired valve opening at any time. However, frictional forces and stiction in the valve leads to certain delay in the actual valve opening. The relationship between the actual valve opening and the desired valve opening is modelled as a first order process, with a first order time delay:

$$\tau_V \frac{d[\%\mathrm{valve}(t)]}{dt} + \%\mathrm{valve}(t) = \%\mathrm{valve}_{\mathrm{desired}}(t) \qquad (5)$$

where $\tau_V$ is the valve time delay due to stiction or friction. If there is no time delay, $\tau_V = 0$, and $\%\mathrm{valve} = \%\mathrm{valve}_{\mathrm{desired}}$.

Next, the measuring device in a typical feedback controller is usually some sort of meter or sensor, depending on the nature of the controlled variable being measured. In the direct operated gas pressure regulator, the measuring device is the diaphragm itself. Some direct operated gas regulators use an additional sensing line to measure the outlet pressure at a location slightly downstream of the regulator itself. Ignoring the slight loss in pressure due to small piping section, there will be delays in the pressure measured as compared to the actual outlet pressure. As such, the relationship between the measured pressure and actual outlet pressure is modeled as a first order process, with a first order time delay:

$$\tau_M \frac{d[P_2^{\mathrm{measured}}(t)]}{dt} + P_2^{\mathrm{measured}}(t) = P_2(t) \qquad (6)$$

where $\tau_M$ is the measurement time delay due to possible additional sensing line. If there is no additional sensing line, and no delays in the measurement, then $\tau_M = 0$, and $P_2^{\mathrm{measured}}(t) = P_2(t)$.

## Parameter Estimation

Consider a direct operated pressure regulator. Given the outlet pressure and valve opening profiles with time (sufficiently high frequency), for known inlet conditions, we wish to obtain the measurement time constant ($\tau_m$), valve time constant ($\tau_v$), and proportionality constant ($K_c$) of the feedback controller.

Assumptions:

1) First order measurement time lag
2) First order valve opening characteristics
3) Proportional only controller

The objective equation to be minimized is the total squared error(TSE) in the valve percentage opening:

$$\mathrm{TSE} = \sum_{i=1}^{n} \left(\%\mathrm{valve}_{\mathrm{empirical},i} - \%\mathrm{valve}_{\mathrm{predicted},i}\right)^2 \qquad (7)$$

where n is the number of discretized points (time).

## Case Study

The empirical data from the study conducted by Zhang and Li on a pressure regulator used for an agricultural application was used in this study. (Zhang, C., and Li, G., 2015) Considering the non-availability of operational data pertaining to a gas pressure regulator in the open literature, the set of data from this study was the best choice. The following figures represent the raw data from the original article:

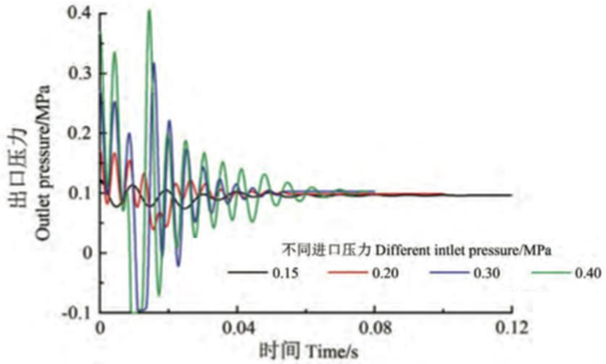

*Figure 2. Outlet Pressure with 0.1 MPa Setpoint*

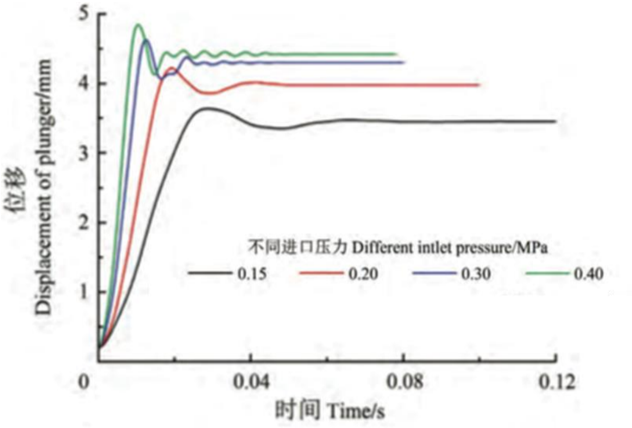

*Figure 3. Displacement of Plunger with 0.1 MPa Setpoint*

The gas pressure regulator being tested by Zhang and Li is a direct operated gas pressure regulator. (Zhang, C., and Li, G., 2015) The allowable plunger displacement path is 5 mm, where it is fully open around 0.2 mm, as depicted at the start of figure 3, and is fully closed at 5 mm.

The raw data from pictorial graphs are digitized using "Graph Digitizer" programme, and linear interpolation was carried out using Microsoft Excel "FORECAST" command. Linear interpolation is carried out so as to achieve equally time-spaced data for both pressure and plunger displacement profiles. As a result, linear interpolation becomes fairly accurate, as the individual segments of the curve between any two data points selected are almost linear. After linear interpolation, the data was extrapolated following the steady state condition up to 0.08s.

For the case of inlet pressure 0.3MPa, the outlet pressure profile is digitized and interpolated linearly, as seen in the figure below.

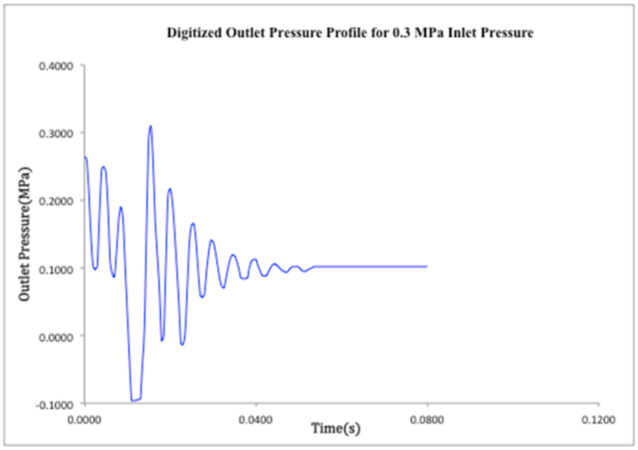

*Figure 4. Digitized Outlet Pressure Profile for 0.3 MPa Inlet Pressure*

The plunger displacement profile for the inlet pressure 0.3 MPa is digitized and interpolated linearly as seen in the figure below.

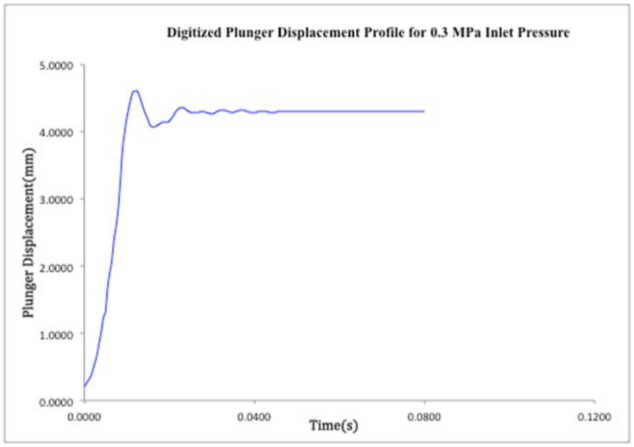

*Figure 5. Digitized Plunger Displacement Profile for 0.3 MPa Inlet Pressure*

To use the previously decribed equations, the plunger displacement data has to be converted to a percentage valve opening data. Since 0.2 mm is the point where the valve is fully open, and 5 mm is the point where the valve is fully closed, the percentage valve opening is expressed as:

$$\%\mathrm{valve}(\mathrm{t}) = 1 - \frac{\mathrm{displacement}(\mathrm{t}) - \text{fully open displacement}}{\text{fully closed displacement} - \text{fully open displacement}} \tag{8}$$

$$\%\mathrm{valve}(\mathrm{t}) = 1 - \frac{\mathrm{displacement}(\mathrm{t}) - 0.2}{4.8} \tag{9}$$

With the above relationship, the valve opening percentage profile is plotted as shown below:

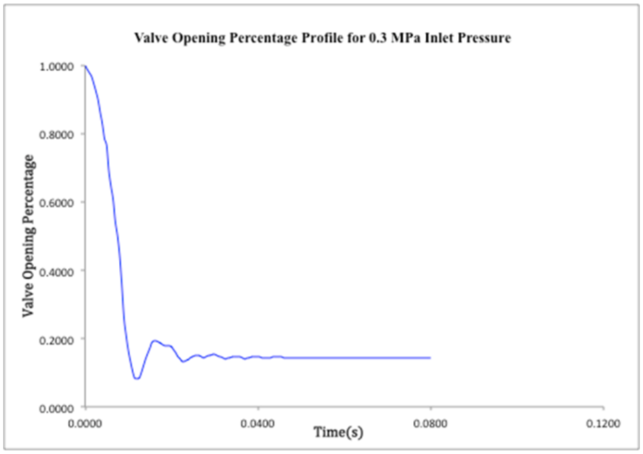

*Figure 6. Valve Opening Percentage Profile for 0.3 MPa Inlet Pressure*

The optimal values for each parameter whereby the error value from the objective equation is minimized was solved by GAMS to be:

$$\mathrm{K_C} = 1.3\ \mathrm{mm/MPa}$$

$$\tau_\mathrm{V} = 0.001\ \mathrm{s}^{-1}$$

$$\tau_\mathrm{M} = 0.007\ \mathrm{s}^{-1}$$

$$\mathrm{TSE} = 0.662$$

An initial Order of Magnitude judgment on the values of the parameters suggests that the values are logical. Considering the units of the $K_c$, and that the total plunger movement displacement is 4.8 mm, a value lower than this suggests good modelling results. If the value is larger than this, if likely reflects over sensitive regulation, leading to cyclical fully opening and closing of the valve, which is not reflected in the empirical data. The time delay values are also acceptable, being less than 10% of the total time of the experiment.

## Model Validation

A secondary set of empirical data at new inlet pressure conditions is digitized, and compared with the predicted response obtained from the model under the same parameters. This comparison is shown in the following figures:

The accuracy of fit for the outlet pressure profile was not good. However, it can be observed that the general pattern of the outlet pressure movement is similar. The predicted outlet pressure rises as the empirical outlet pressure increases, and vice versa. Both the empirical and predicted models reflect initial oscillation, and stabilization to a steady state at approximately 0.07s around the outlet setpoint pressure of 0.1 MPa.

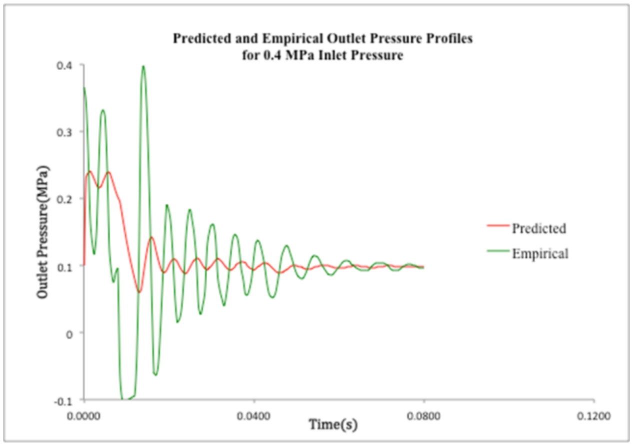

*Figure 7. Predicted and Empirical Outlet Pressure Profiles for 0.4 MPa Inlet Pressure*

The raw data corresponding to plunger displacement is digitized:

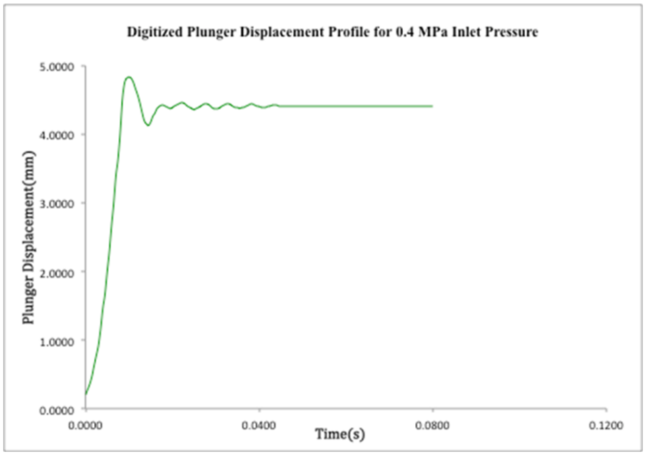

*Figure 8. Digitized Plunger Displacement Profile for 0.4 MPa Inlet Pressure*

Using Eq. 9, the empirical valve opening percentage profile is plotted together with the predicted profile in the following figure:

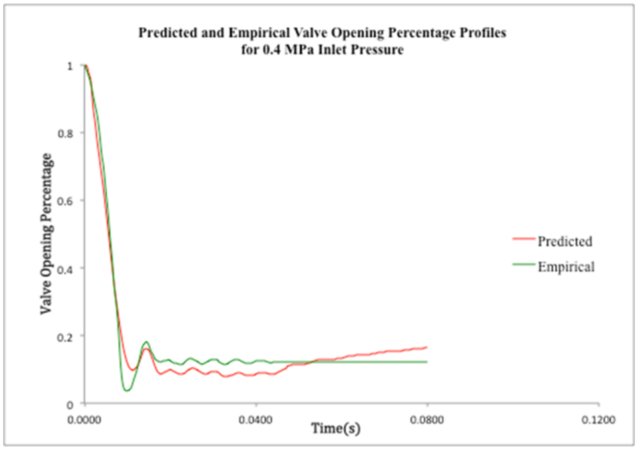

*Figure 9. Predicted and Empirical Valve Opening Percentage Profiles for 0.4 MPa Inlet Pressure*

From the figure above, the model is reasonably well fitted. The general movement of the valve opening percentage is similar in both models. However, it is noted that the predicted model does not settle down to a final steady state value as quick as the empirical data. However, the error tolerance is still acceptable, as seen by the low sum of squared error value. The data shown in this figure validates the model parameters to a certain extent, as well as the overall modelling approach.

The model predicts the valve opening profile quite well. However, the significant error in the estimation of outlet pressure indicates that the relation between valve opening and the outlet pressure needs to be revised in magnitude keeping the trend intact.

## Conclusions

A new approach has been suggested to model a direct operated gas pressure regulator in this study. This underlying idea behind this approach is to use to model the gas pressure regulator as a control valve with a feedback controller. This model can be represented using block diagrams in a process control system.

In light of the general lower performance level of a direct operated gas regulator, pilot operated gas regulators are more common in recent times. As such, a next step to this study could be the modelling of a pilot operated gas pressure regulator. A pilot controlled gas regulator consists of an addition pilot regulator, feeding an amplified sensed error to the main regulator, hence enhancing the performance. Therefore, it can be modelled as two connected direct operated regulators. (Emerson manual)

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