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Master's in Automation and IT

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Valve Model

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1 Problem Statement

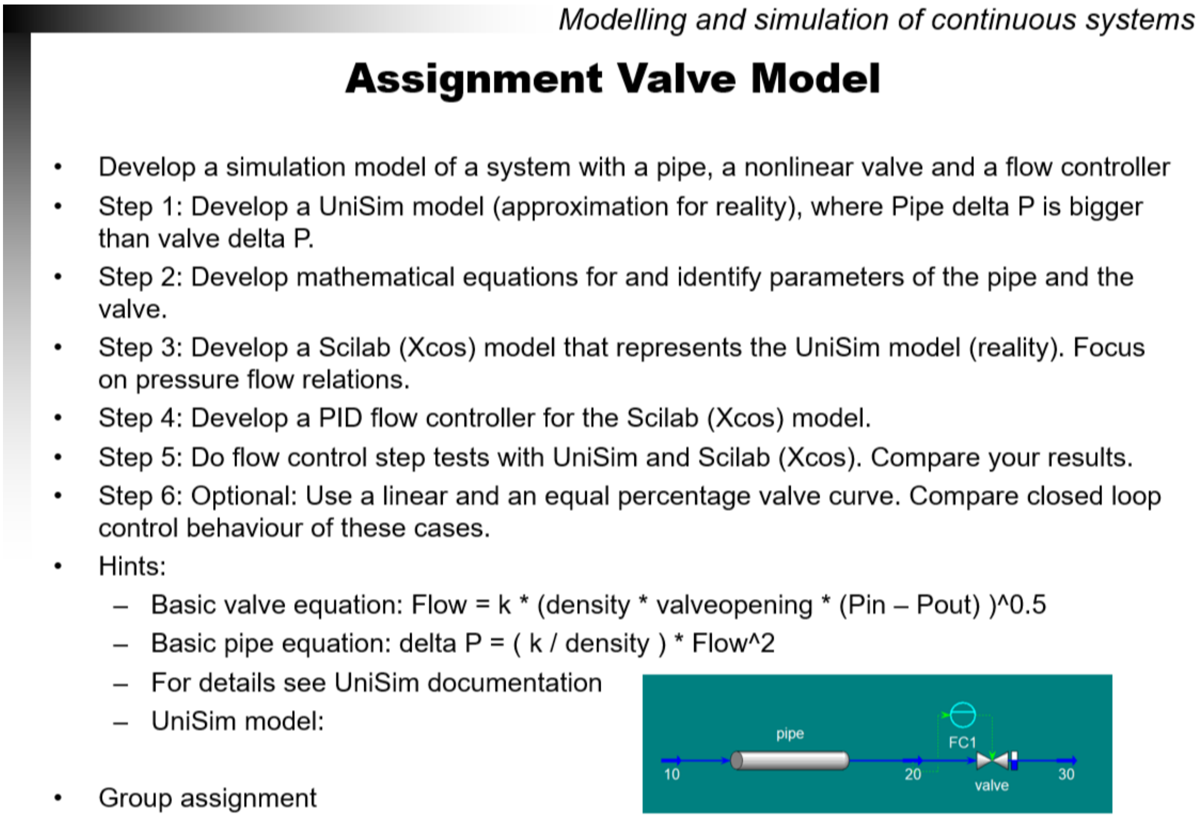


Figure 1: Problem Statement

2 Introduction

In this assignment we are implementing a simple model to simulate a system consisting of a pipe, a non-linear equal percentage valve and a flow controller using UniSim and in Simulink. The model is build to approximately represent the reality, where pipe delta P is bigger than valve delta P.

3 Procedure/ Methods

The study was conducted in UniSim and in Simulink.

The UniSim software package significantly enhances the modelling of live and offline process unit design and optimization applications and aids in determining work flow, equipment requirements, and implementation requirements for a specific process. Users may simply collect and share process information, enhance plant performance, and get the most out of their simulation investments.

Simulink is a simulation environment useful for design and analysis of control system models developed in Simulink.It aids in the automated tuning of arbitrary SISO and MIMO control structures, such as PID controllers. PID autotuning can be implemented in embedded software to compute PID gains in real time.

The procedural steps taken were:

1. Developing UniSim Model:
   A model setup consisting of a pipe, non-linear equal percentage valve and a actuator which nearly represents a real world system.

2. Developing Mathematical equations and parameters identification:
   The mathematical equations have been obtained which is further used to develop the model in MATLAB. The parameters are estimated using Moore-Penrose Pseudo Inverse method.

3. Developing a mathematical model in Simulink :
   Based on the above obtained mathematical equations and parameters, the mathematical model of the system is developed on Simulink, which represents the UniSim model.

4. Analysis :
   Based on the developed model in UniSim and Simulink, analysis has been done.

4 Developing a Unisim Model

For simulation modelling, we are utilizing the UniSim model of a system with a pipe and a non-linear (equal percentage control valve) with a PID flow controller.The behaviour of this continuous process is studied in order to analyse the various components of the system and create a mathematical model in Simulink simulation environment. The design parameters of the primary components of the UniSim model are mentioned below.

1. Design structure

   - **Pipe**
     We have used a pipe of length 50 m, inner diameter of 20 mm and outer diameter of 30 mm. The pipe flow model has been set to Simple Pipe Friction model method to calculate the pressure drop. We have provided pressure at inlet 301.3 kPa.

   - **Valve**
     Equal percentage valve has been chosen.The various specifications for the valve and the corresponding curve is shown in the figures below.

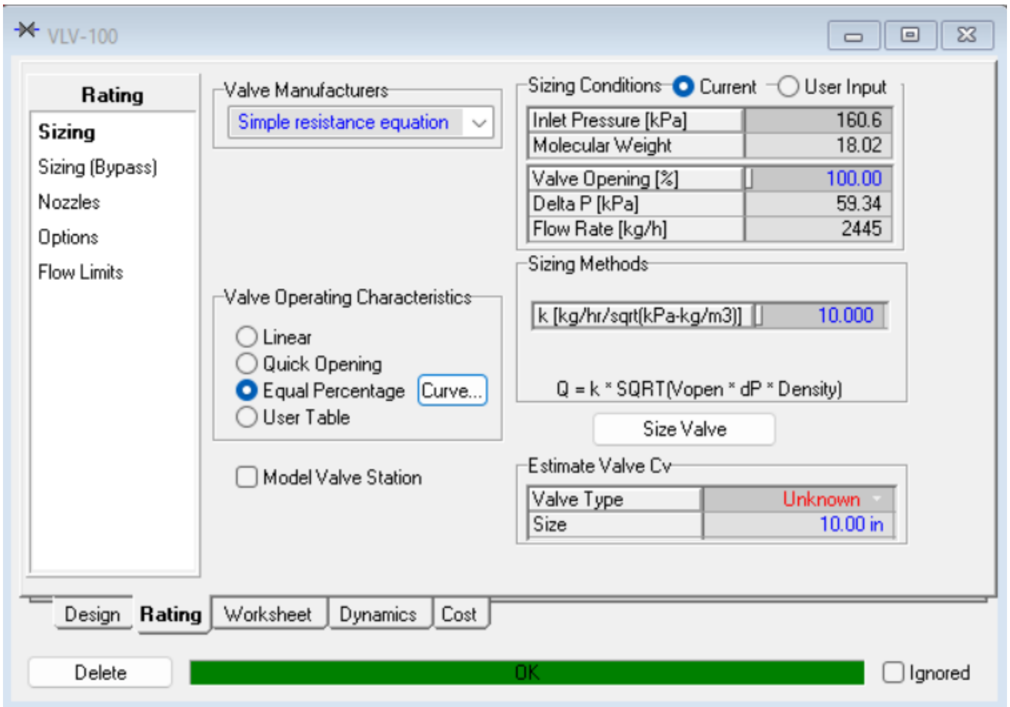


Figure 2: Valve Specifications

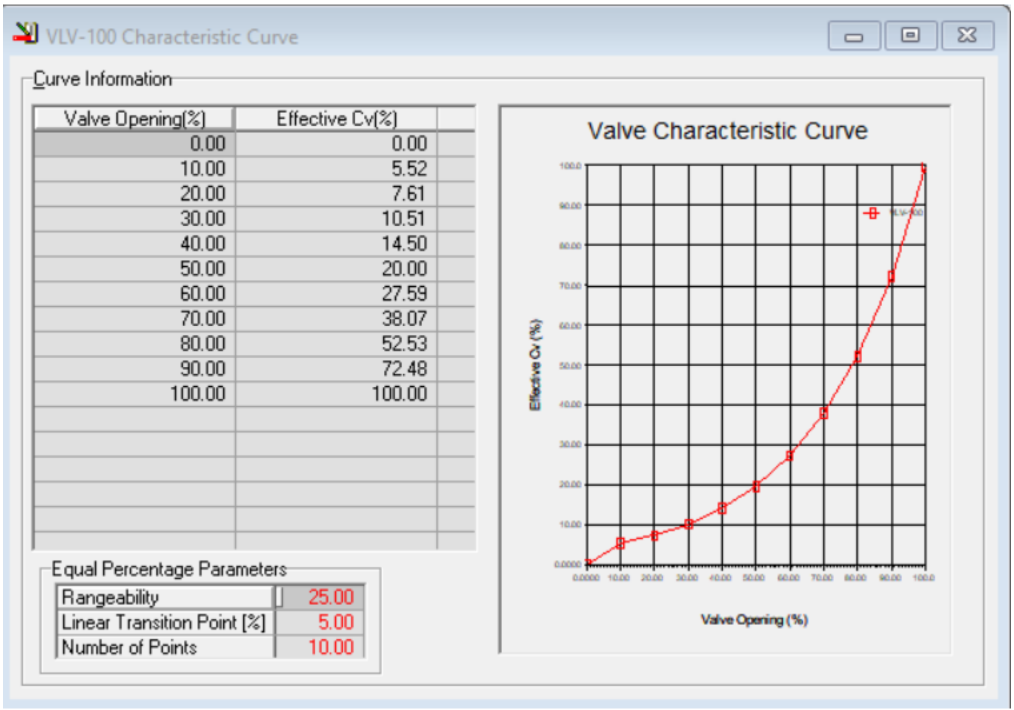


Figure 3: Valve Curve

- **Flow controller**
  We attached the controller to the pipe's output as our process variable source and chose mass flow to measure. The output target object has been chosen as the valve.

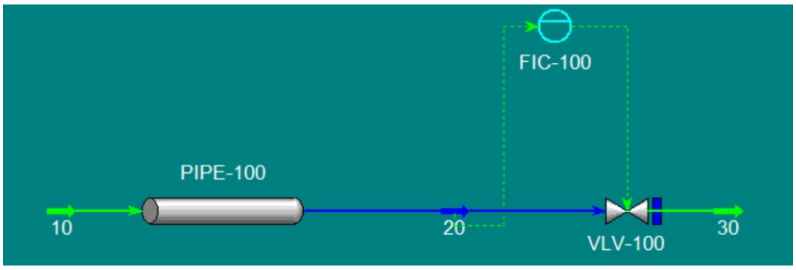


Figure 4: UniSim Model

2. Procedure

- In the model P_1 and P_3 are constant and the system is modelled such that pipe delta P is bigger than valve delta P or in other words $(P_2 - P_1) > (P_3 - P_2)$.
- Then we observed the mass flow PV for different OP values. The OP values were incremented in 10% range.

3. Observation

OP(%)	PV (kg/hr)	P1 (kPa)	P2 (kPa)	P3 (kPa)	$\Delta Pp(P1-P2)$	$\Delta Pv(P2-P3)$	Y (Calculated Kv)	Actual Kv
0	0	301.3	301.3	101.3	0	2	0	0
0.05	210.35	301.3	300.1	101.3	0.012	1.988	4.717743515	4.69847577235208
0.1	246.84	301.3	299.9	101.3	0.014	1.986	5.538930498	5.51891864584486
0.15	289.55	301.3	299.3	101.3	0.02	1.98	6.507152339	6.48262638677105
0.2	339.47	301.3	298.6	101.3	0.027	1.973	7.642542416	7.61461575486351
0.25	397.73	301.3	297.6	101.3	0.037	1.963	8.976937477	8.94427190999916
0.3	465.54	301,.3	296.2	101.3	0.051	1.949	10.54510923	10.5061112176151
0.35	544.2	301.3	294.3	101.3	0.07	1.93	12.38739205	12.3406772544002
0.4	635.04	301.3	291.8	101.3	0.095	1.905	14.54968502	14.4955932735539
0.45	739.3	301.3	288.4	101.3	0.129	1.871	17.09164298	17.0267984504157
0.5	857.98	301.3	282.7	101.3	0.186	1.814	20.14459419	20.0000000000000
0.55	991.63	301.3	278.2	101.3	0.231	1.769	23.57684784	23.4923788617604
0.6	1140	301.3	270.7	101.3	0.306	1.694	27.69798325	27.5945932292243
0.65	1301.8	301.3	261.4	101.3	0.399	1.601	32.53483445	32.4131319338552
0.7	1474.3	301.3	250.2	101.3	0.511	1.489	38.206611	38.0730787743176
0.75	1653.3	301.3	237	101.3	0.643	1.357	44.88091908	44.7213595499958
0.8	1833.3	301.3	222.2	101,3	0.791	1.209	52.72546129	52.5305560880754
0.85	2008	301.3	206.4	101.3	0.949	1.051	61.93873773	61.7033862720010
0.9	2171.1	301.3	190.4	101.3	1.109	0.891	72.73458669	72.4779663677696
0.95	2317.8	301.3	174.9	101.3	1.264	0.736	85.43524149	85.1339922520785
1	2444.9	301.3	160.6	101.3	1.407	0.593	100.4000095	100

Table 1: Pressure change at different OP values

The below table shows the values of pressure at points P1, P2 and P3 and the PV. It also shows the pressure drop in the pipe and the valve. The values are obtained at different OP values with step signal as input. At OP = 1, it can be seen that the Pipe delta P is greater than valve delta P.

5 Developing Mathematical equations and Parameter Identification

The basic valve equation is given by:

$$Q = K_v \cdot \sqrt{\delta \cdot v \cdot P_{in} - P_{out}} \tag{1}$$

Rewriting the valve equation as follows:

$$Q = K_v \cdot \sqrt{\delta \cdot v \cdot P_2 - P_3} \tag{2}$$

where,

$\Delta P_v = P_2 - P_3 =$ Pressure drop across the valve
$Q =$ Flow
$v =$ Valve opening
$\delta =$ Density of the medium (in our case, "water")
$K_v =$ Valve coefficient

The basic pipe equation is given by:

$$\Delta P_p = \frac{K_p}{\delta} \cdot Q^2 \tag{3}$$

Rewriting the pipe equation, we get:

$$Q = \sqrt{\Delta P_p \cdot \frac{\delta}{K_p}} \tag{4}$$

where,

$\Delta P_p = P_1 - P_2 =$ Pressure drop across the pipe

Equating equations (1) and (3), we get:

$$K_v \cdot \sqrt{\delta \cdot v \cdot \Delta P_v} = \sqrt{\Delta P_p \cdot \frac{\delta}{K_p}} \tag{5}$$

Squaring both sides,

$$K_v^2 \cdot \delta \cdot v \cdot \Delta P_v = \Delta P_p \cdot \frac{\delta}{K_p} \tag{6}$$

Since $\Delta P_p = P_1 - P_2$ and $= P_2 = \Delta P_v + P_3$,therefore,

$$K_v^2 \cdot \delta \cdot v \cdot \Delta P_v = P_1 - (P_3 + \Delta P_v) \cdot \frac{\delta}{K_p} \tag{7}$$

$$K_v^2 \cdot v \cdot \Delta P_v \cdot K_p = P_1 - P_3 - \Delta P_v \tag{8}$$

$$K_v^2 \cdot v \cdot \Delta P_v \cdot K_p + \Delta P_v = P_1 - P_3 \tag{9}$$

$$\Delta P_v[K_v^2 \cdot v \cdot K_p + 1] = P_1 - P_3 \tag{10}$$

$$\boxed{\Delta P_v = \frac{P_1 - P_3}{1 + K_v^2 v K_p}} \tag{11}$$

The equation for ΔP_v is used further in developing the model in Simulink.

5.1 Parameter estimation

We have obtained the PV values for given OP values from the UniSim model. The third order polynomial gives the values of flow with respect to different values of OP. Considering the basic valve equation,

$$Q = Kv\sqrt{\rho \cdot v \cdot \Delta P} \tag{12}$$

$$Q = Kv_{\max} \cdot f(v) \cdot \sqrt{\rho \cdot \Delta P} \tag{13}$$

$$\frac{Q}{\sqrt{\rho \cdot \Delta P}} = Kv_{\max} \cdot f(v) \tag{14}$$

Above equation can be represented by

$$Y = A \cdot X \tag{15}$$

where,

Y = PV values
A = valve equation coefficients
X = matrix of 3rd order polynomial

$$Y = a_3 x^3 + a_2 x^2 + a_1 x^1 + a_0 \tag{16}$$

$$A = Y \cdot X^{\text{-1}} \tag{17}$$

Rearranging the above equation we get the Pseudoinverse

$$A = (Y^{\mathrm{T}}) \cdot (X^{\text{-1}} \cdot X^{\mathrm{T}}) \tag{18}$$

Representing equation (15) in matrix form, we get,

$$\begin{bmatrix} \frac{Q_0}{\sqrt{\rho * \Delta P}} \\ \frac{Q_1}{\sqrt{\rho * \Delta P}} \\ \frac{Q_2}{\sqrt{\rho * \Delta P}} \\ . \\ . \\ . \\ \frac{Q_{10}}{\sqrt{\rho * \Delta P}} \end{bmatrix} = \begin{bmatrix} {x_0}^3 & {x_0}^2 & x_0 & 0 \\ {x_1}^3 & {x_1}^2 & x_1 & 1 \\ {x_2}^3 & {x_2}^2 & x_2 & 1 \\ . & & & \\ . & & & \\ . & & & \\ {x_{10}}^3 & {x_{10}}^2 & x_{10} & 1 \end{bmatrix} * \begin{bmatrix} a_3 & a_2 & a_1 & a_0 \end{bmatrix} \tag{19}$$

Pseudoinverse can be calculated in MATLAB with command

$$A = X \backslash Y \tag{20}$$

```
X = [0,0,0,1;
0.000125,0.0025,0.05,1;
0.001,0.01,0.1,1;
0.003375,0.0225,0.15,1;
0.008,0.04,0.2,1;
0.015625,0.0625,0.25,1;
0.027,0.09,0.3,1;
0.042875,0.1225,0.35,1;
0.064,0.16,0.4,1;
0.091125,0.2025,0.45,1;
0.125,0.25,0.5,1;
0.166375,0.3025,0.55,1;
0.216,0.36,0.6,1;
0.274625,0.4225,0.65,1;
0.343,0.49,0.7,1;
0.421875,0.5625,0.75,1;
0.512,0.64,0.8,1;
0.614125,0.7225,0.85,1;
0.729,0.81,0.9,1;
0.857375,0.9025,0.95,1;
1,1,1,1;
];
```

```
Y = [0;
4.717743515;
5.538930498;
6.507152339;
7.642542416;
8.976937477;
10.54510923;
12.38739205;
14.54968502;
17.09164298;
20.14459419;
23.57684784;
27.69798325;
32.53483445;
38.206611;
44.88091908;
52.72546129;
61.93873773;
72.73458669;
85.43524149;
100.4000095;
];
A = X\Y
```

```
A =

  147.9155
  -99.7141
   50.4177
    0.9006
```

Figure 6: MATLAB results

After calculating Pseudoinverse the values obtained are

a_3 = 147.9155 a_2 = -99.7141 a_1 = 50.4177 a_0 = 0.9006

From the above coefficients, we can get the Kv in terms of OP.

$$\boxed{Kv = 147.9155 * x_3 - 99.7141 * x_2 + 50.4177 * x + 0.9006} \tag{21}$$

Identification of Kv_{max} :

Kv_{max} can be calculated by substituting the value of x = 1

$$Kv_{max} = 147.9155 * 1^3 - 99.7141 * 1^2 + 50.4177 * 1 + 0.9006 \tag{22}$$

$$\boxed{Kv_{max} = 99.5197} \tag{23}$$

Identification of Kp :

$$\Delta P_p * \delta = K_p * Q^2 \tag{24}$$

The above equation can be represented as:

$$Y = K_p * X \tag{25}$$

where,
Y= $\Delta P_p * \delta$
X= Q^2

K_p is calculated using the pseudocode command in MATLAB:

$$K_p = X \backslash Y \tag{26}$$

The obtained value of K_p from MATLAB is as follows:

$$\boxed{\mathrm{K}_p = 0.000235} \tag{27}$$

5.2 Developing first order transfer function of valve

The first order equation for the valve is given by:

$$\tau \frac{dy}{dt} + y = ku \tag{28}$$

As, the input to the valve is PV which is the mass flow and can be represented by Q. And, the output for the valve is OP which is the actuator travel and can be represented by H.

Thus, the equation would be:

$$\tau \frac{dH}{dt} + H = kQ \tag{29}$$

Where τ is the time constant of the valve and k is the gain of the process

Taking the Laplace transform of the above transfer function, we would get:

$$\frac{Q}{H} = \frac{k}{\tau s + 1} \tag{30}$$

This is the transfer function of the first order system.

Now, from the UniSim we identified the that the time constant value (τ) is 5sec or 0.0833 min.
Therefore,

$$\frac{Q}{H} = \frac{k}{5s+1} \tag{31}$$

This transfer function would be used for mathematical modelling of the UniSim model.

6 Developing a Simulink Model representing the Unisim model

After developing mathematical equations and estimating various parameters, we used these to develop the model in Simulink.

Component Identification

6.1 PI controller along with Antiwindup

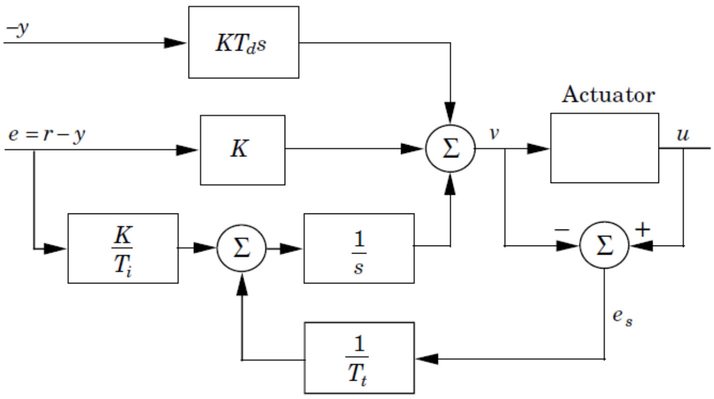


Figure 7: Controller back calculation [1]

The PI controller is implemented along with Anti-windup method. This anti-windup technique is implemented using Karl Astrom's back calculation method suggested in the book *Advanced PID Control by Karl J. Astrom*

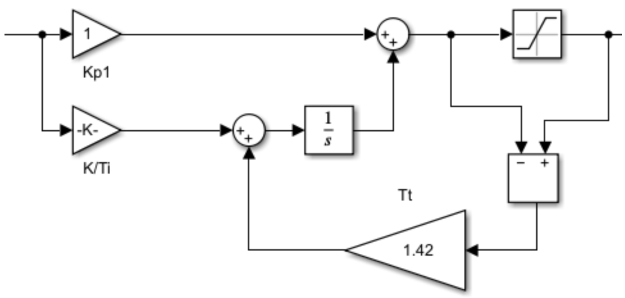


Figure 8: PI implementation along with back calculation

When PI was implemented without the back calculation method, there was a risk of integrator wind-up. In other words, the controller output could transiently

exceed the saturation on the actuator, the linear loop performance may seriously degrade. That is, the state variables in both the controller and the plant wind-ups or runs-away. So, we have implemented the controller considering this situation of wind-up which could possibly occur in the future.
Here, in our implementation we ensure that the signal settles on a value just outside the saturation limit, and that the control signal can react quickly as the error varies over time. The integrator will not wind up as a result of this. The feedback gain, $1/T_t$, governs the rate at which the controller output is reset, where T_t is the time constant that dictates how quickly the integral component is reset. This is also known as the tracking time constant.

6.2 Actuator

The implementation of actuator is done along with auto-manual selector switch to make it more similar to the real world simulation done on Unisim.

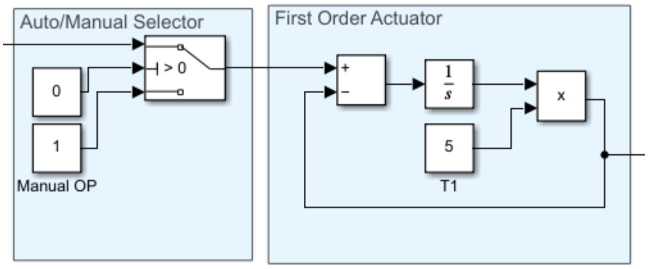


Figure 9: Actuator

The auto-manual switch is done using a simple switching algorithm. If the control input has 0 as input then the system is in manual mode and if it has 1 as input then the system is in automatic mode.

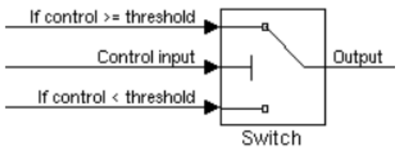


Figure 10: Switch Concept [2]

The first order equal percentage actuator is implemented using the equation

$$T_1 \frac{dV}{dt} + V = OP \tag{32}$$

6.3 ΔP Calculation

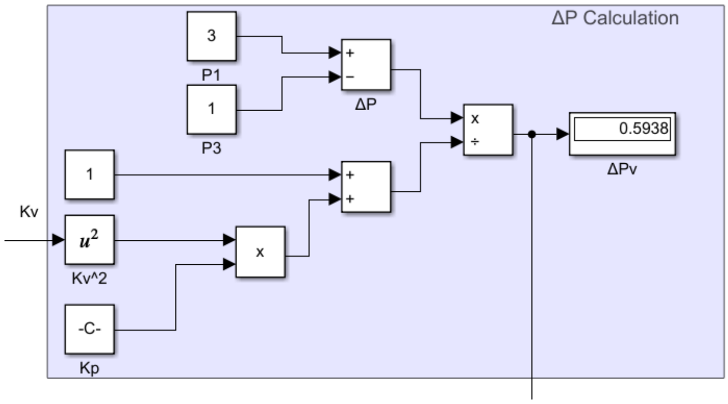


Figure 11: Non-linear equal percentage valve

We can express the delta pressure variation across the valve using the relation obtained from the calculations earlier.

$$\Delta P_v = \frac{P_1 - P_3}{1 + K_v^2 v K_p} \tag{33}$$

The variable Kv is fed to the ΔP calculation.

6.4 Flow calculation

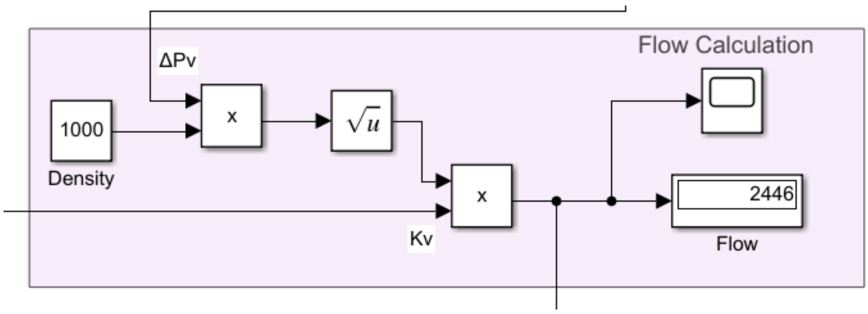


Figure 12: Pressure Flow relation

The flow is also calculated at each step, just like in the ΔP calculation. The flow through the valve is given by the following equation.

$$Q = Kv\sqrt{\rho \cdot v \cdot \Delta P} \tag{34}$$

The ΔP and the Kv calculated earlier are used here in the calculation of the flow or PV.

7 System behaviour of Simulink model

7.1 Open loop implementation

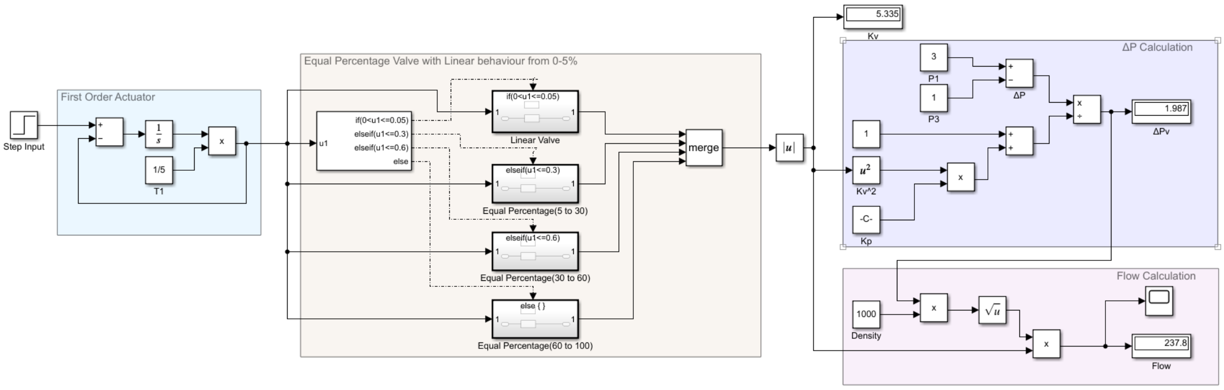


Figure 13: Open loop implementation

OP(%)	Unisim PV(kg/hr)	Simulink PV(kg/hr)	Unisim Time constant (seconds)	Simulink Time constant (seconds)	Unisim -Delta Pv=p2-p3	Simulink Delta Pv=p2-p3	Y (Calculated Kv)	Actual Kv
0	0	0	0	0	2	2	0	0
0.05	210.35	210.4	5.4	5.4	1.988	1.99	4.717743515	4.69847577235208
0.1	246.84	246.9	6.1	5.4	1.954	1.986	5.538930498	5.51891864584486
0.15	289.55	289.5	6	5.4	1.899	1.98	6.507152339	6.48262638677105
0.2	339.47	339.4	6.1	5.5	1.827	1.973	7.642542416	7.61461575486351
0.25	397.73	397.8	5.8	5.4	1.742	1.963	8.976937477	8.94427190999916
0.3	465.54	465.5	6	5.66	1.648	1.949	10.54510923	10.5061112176151
0.35	544.2	544.2	6.04	5.4	1.55	1.93	12.38739205	12.3406772544002
0.4	635.04	635.2	6.1	5.4	1.45	1.905	14.54968502	14.4955932735539
0.45	739.3	739.9	5.75	5.4	1.351	1.871	17.09164298	17.0267984504157
0.5	857.98	859.1	6.3	5.271	1.256	1.827	20.14459419	20.0000000000000
0.55	991.63	992.8	5.74	5.271	1.165	1.768	23.57684784	23.4923788617604
0.6	1140	1140	5.8	5.271	1.079	1.695	27.69798325	27.5945932292243
0.65	1301.8	1304	5.9	5.271	0.999	1.6	32.53483445	32.4131319338552
0.7	1474.3	1476	5.46	5.2	0.925	1.488	38.206611	38.0730787743176
0.75	1653.3	1653	5.7	5.271	0.857	1.358	44.88091908	44.7213595499958
0.8	1833.3	1833	5.16	5.139	0.795	1.211	52.72546129	52.5305560880754
0.85	2008	2008	5.4	5.139	0.737	1.052	61.93873773	61.7033862720010
0.9	2171.1	2172	5.7	5.007	0.685	0.891	72.73458669	72.4779663677696
0.95	2317.8	2320	5	4.875	0.637	0.7355	85.43524149	85.1339922520785
1	2444.9	2446	5.4	4.744	0.593	0.5938	100.4000095	100

Table 2: Open loop response for Unisim and Simulink

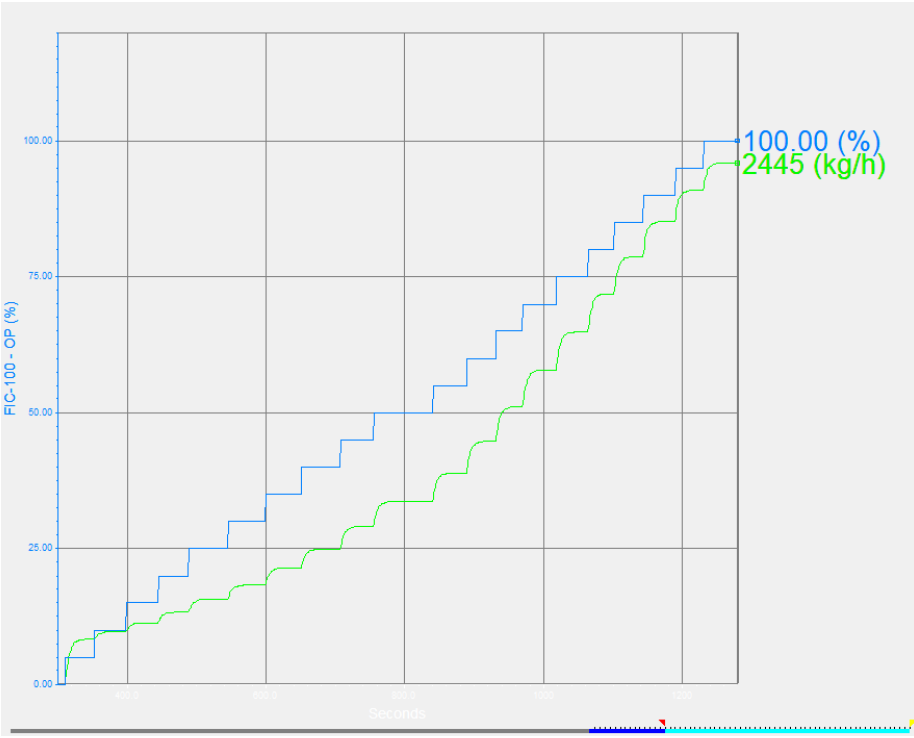


Figure 14: Open loop step test - Unisim

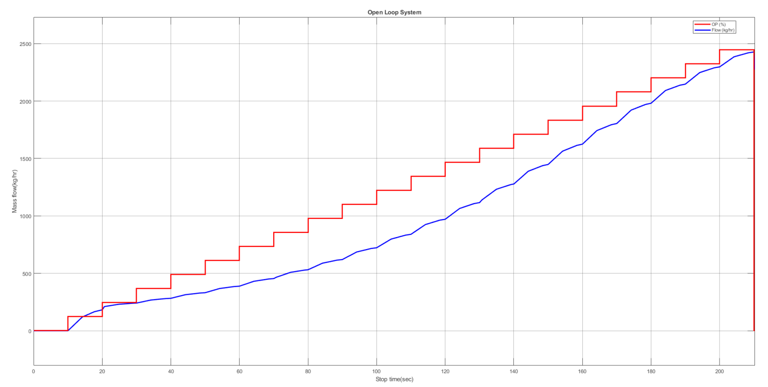


Figure 15: Open loop step test - Simulink

We can observe that the behaviour of our model emulates the same as UniSim model in open loop experimentation. This is explained in the means of step test and equal percentage valve curve can be observed in this way.

7.2 Closed loop implementation

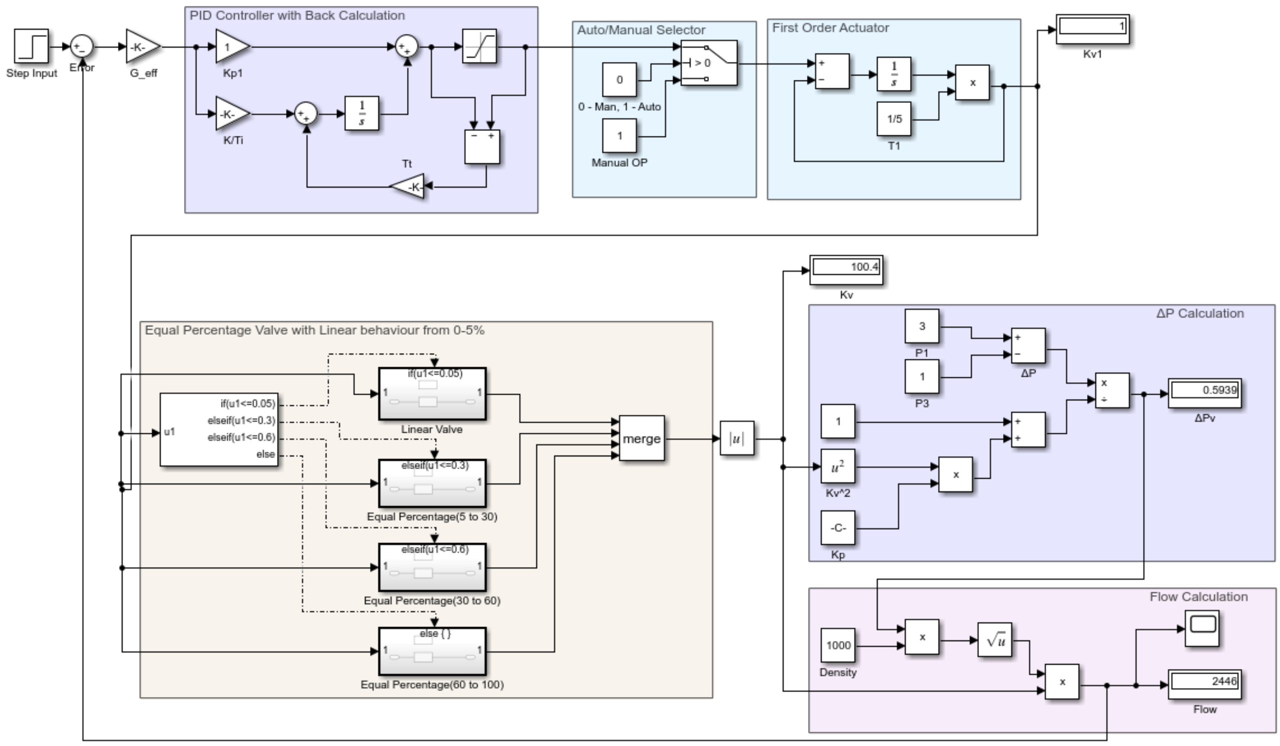


Figure 16: Closed loop system in Simulink

We have implemented the closed loop structure and each section of the system is as explained above.
For the implementation of Kv we initially used the obtained 3rd order polynomial equation found using parameter estimation. i.e.

$$Kv = 149.9029 * x_3 - 101.9745 * x_2 + 51.0768 * x + 0.8337 \tag{35}$$

But using these coefficients we were not able to get values of Kv and correspondingly of flow similar to the values observed from UniSim.
So, to make our system more accurate and comparable to UniSim model, we divided our Kv calculation into 4 parts.

- **0-5% :** The first part is to get linear behaviour in 0-5% range, as in real system using equal percentage valve we observe a linear behaviour initially as equal percentage valve starts initially with a slow increase in flow rate with valve position. The polynomial found for this range is:

$$Kv = 0 * x_3 + 0 * x_2 + 94.3549 * x_1 - 0 \tag{36}$$

- **5-30% :** The polynomial found for this range is:

$$Kv = 39.2014 * x_3 + 16.5594 x_2 - 13.2998 * x_1 + 4.0059 \tag{37}$$

- **30-60% :** The polynomial found for this range is:

$$Kv = 81.8909 * x_3 - 21.1906 * x_2 + 24.6272 * x + 2.8520 \tag{38}$$

- **60-100% :** The polynomial found for this range is:

$$Kv = 303.8396 * x_3 - 444.9016 * x_2 + 298.0721 * x - 56.6199 \tag{39}$$

Unisim-PV(kg/hr)	**Simulink-PV (kg/hr)**	**OP(%)**
0	0	0
210.35	210.4	0.05
246.84	246.9	0.1
289.55	289.5	0.15
339.47	339.4	0.2
397.73	397.8	0.25
465.54	465.5	0.3
544.2	544.2	0.35
635.04	635.2	0.4
739.3	739.9	0.45
857.98	859.1	0.5
991.63	992.8	0.55
1140	1140	0.6
1301.8	1304	0.65
1474.3	1476	0.7
1653.3	1653	0.75
1833.3	1833	0.8
2008	2008	0.85
2171.1	2172	0.9
2317.8	2320	0.95
2444.9	2446	1

Table 3: Closed loop response for both Simulink and Unisim

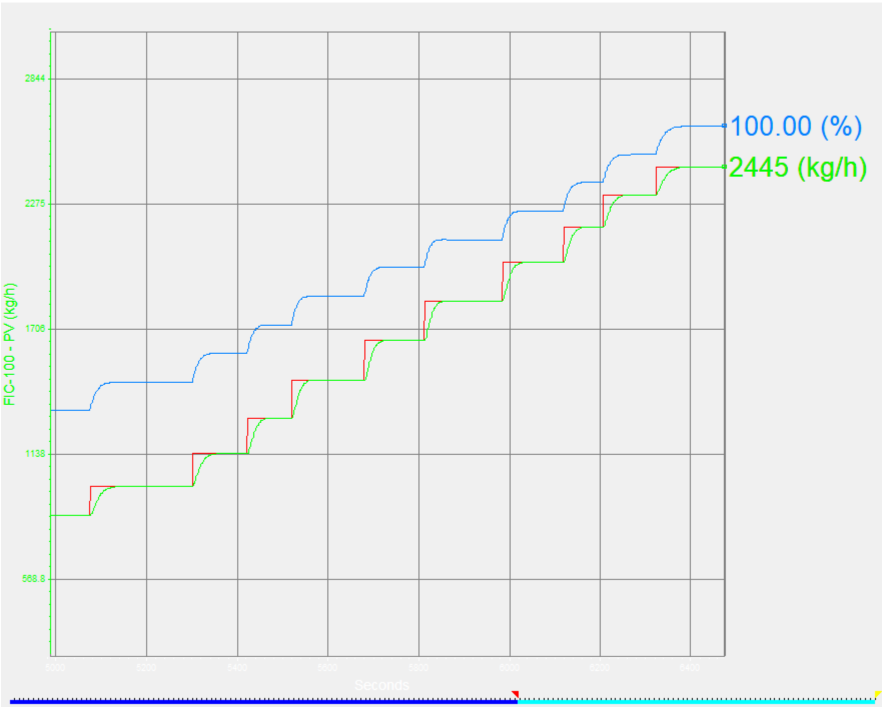


Figure 17: Closed loop step test - UniSim

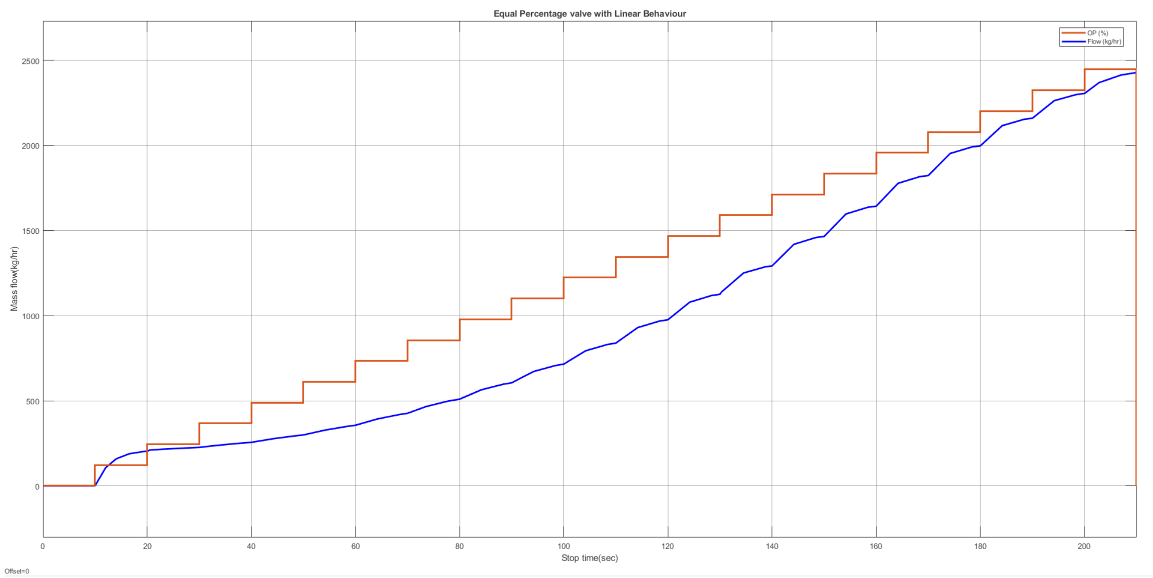
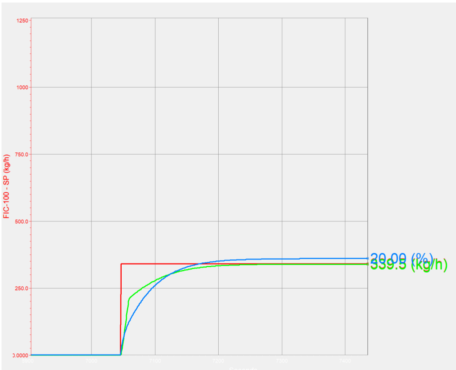
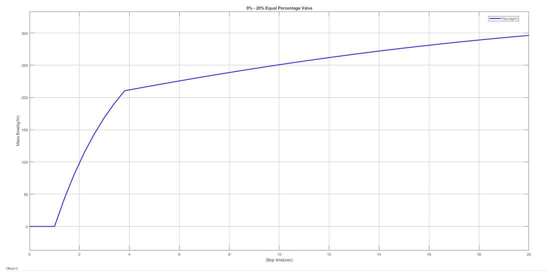


Figure 18: Closed loop step test - Simulink

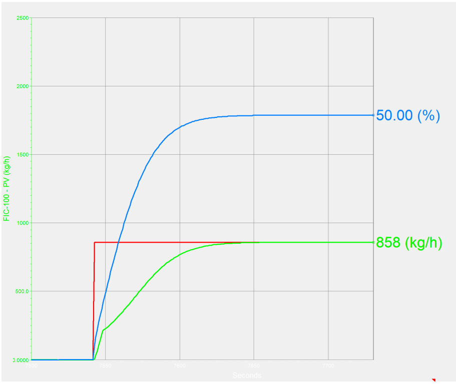


(a) 0-20 UniSim

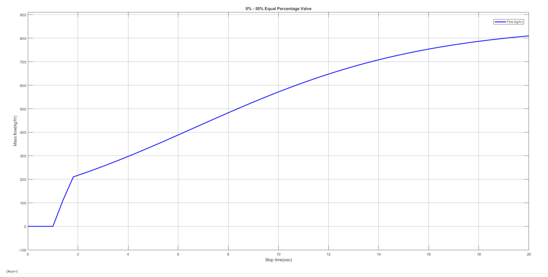


(b) 0-20 Simulink

Figure 19: Comparison between flow in Unisim and Simulink in case of 0-20% OP

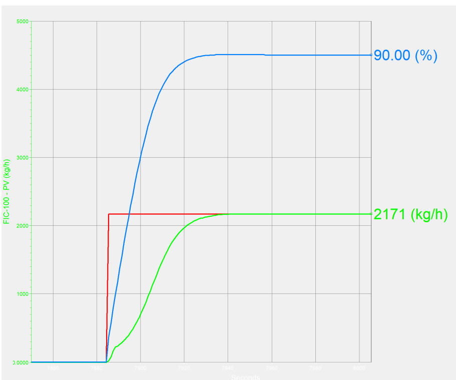


(a) 0-50 UniSim

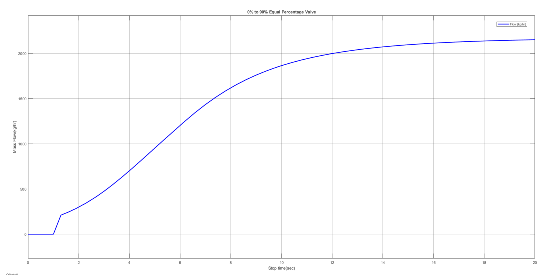


(b) 0-50 Simulink

Figure 20: Comparison between flow in Unisim and Simulink in case of 0-50% OP



(a) 0-90 UniSim



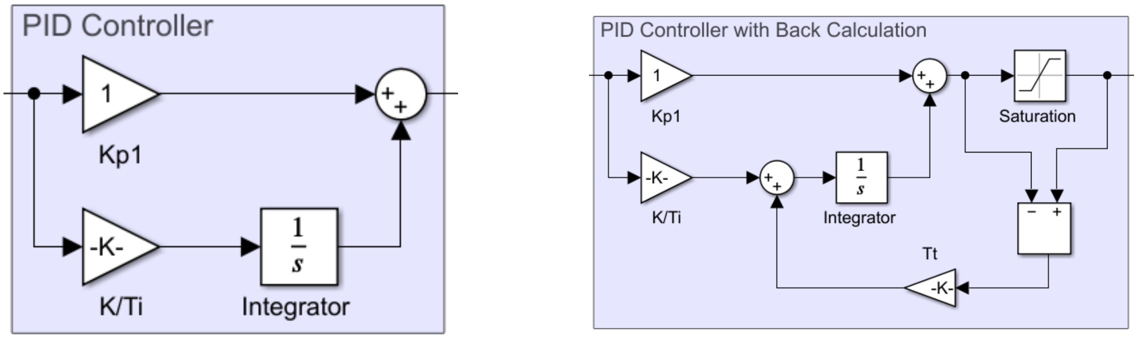
(b) 0-90 Simulink

Figure 21: Comparison between flow in Unisim and Simulink in case of 0-90% OP

It is implied that from the above-mentioned experiments, both the behaviour in UniSim and Simulink are similar and our model developed using Simulink exactly replicates the behaviour we find in the UniSim. We can also see the linear behaviour from 0-5% in the Simulink model, as it is seen in equal percentage valve behaviour in the UniSim.

8 Experimentation

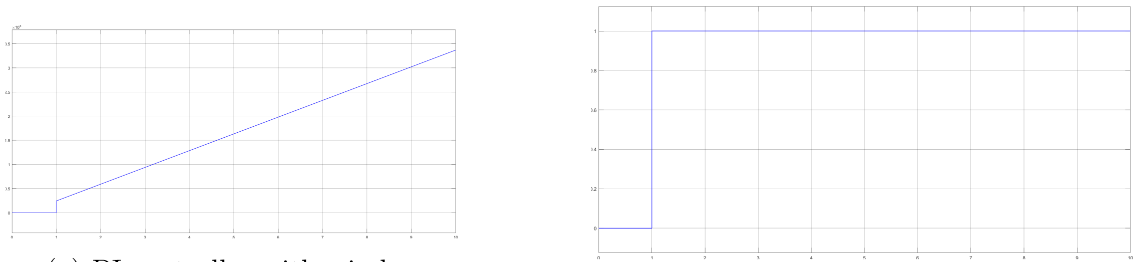
8.1 Comparison between with windup and Anti-windup model



(a) Windup PI System

(b) PI controller with Back calculation

Figure 22: Comparison between windup and back calculation anti-windup implementation



(a) PI controller with windup

(b) PI controller with antiwindup implementation

Figure 23: Comparison between back calculation and override implementation methods

From figure 23 without anti-windup implementation in the system we can observe that the integrator shoots up consequently resulting in the non-ideal flow. While with anti-windup implementation here using back calculation method we can observe a steady controller response and an almost ideal flow.

8.2 Anti-windup using override

An "override" control approach involves choosing between two or more controller output signals, with only one controller having control over a process at a time. All other “deselected” controllers are thus overridden by the selected controller.

We have implemented the override concept, inferring from the implementation done by Karl Astrom in the book PID Controller. It is a special case of implementation of a controller in interacting form.

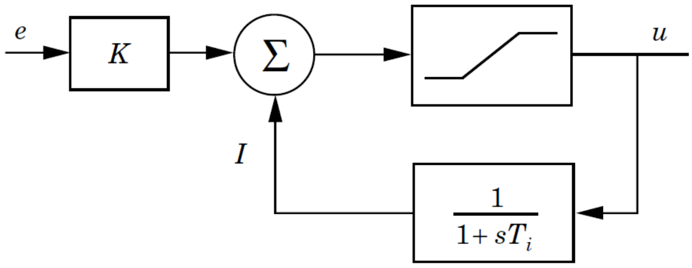


Figure 24: Override concept [1]

To avoid windup in the controller, we have incorporated the saturation in the system. Here, we have our tracking time constant T_t as same as the integration time T_i.

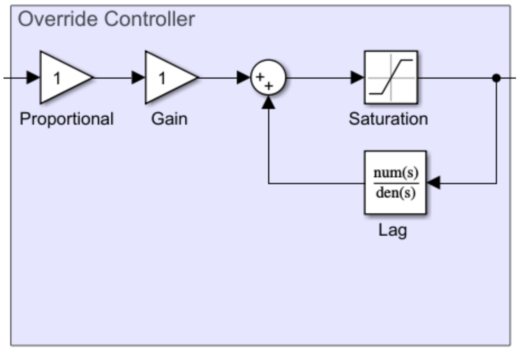
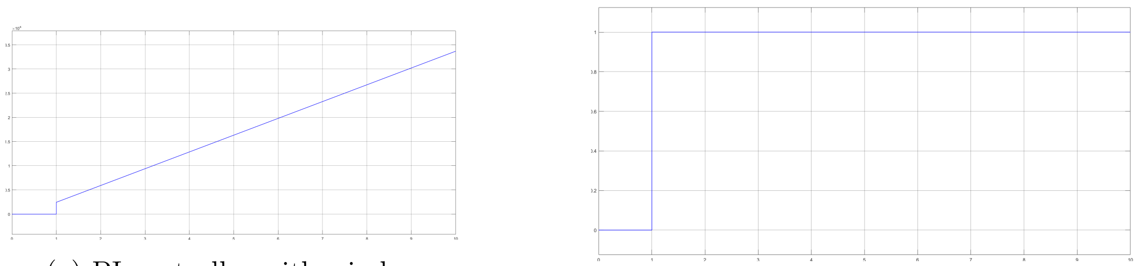


Figure 25: Closed loop with Override control



(a) PI controller with windup

(b) Override Controller without windup issue

Figure 26: Comparison between windup and override implementation comparison

8.3 Implementation using Linear Valve

8.3.1 Parameters and developing equations for linear valve

The parameters Kv and Kp were determined for linear valve, as done previously for equal percentage. The values of PV were obtained at different values of OP and Kv_{max} were calculated using the Pseudoinverse method.

$$Kv_{\max} = 100.4035 \tag{40}$$

Similarly, Kp is also calculated by Pseudoinverse method

$$Kp = 0.000235045 \tag{41}$$

As per calculation of Pseudo-inverse in subsection 2.3. for the valve equation, we calculated the value of Kv in terms of OP. The resultant linear valve equation is as below:

$$Kv = 0.5646 * x_3 - 0.6853 * x_2 + 100.5263 * x - 0.0035 \tag{42}$$

We have changed valve opening characteristic to Linear from Equal percentage while keeping the simple resistance equation for calculating constants in Unisim. We have kept valve Kv constant, similar to equal percentage valve as 100. As far as controller design is concerned, we kept the same parameters of P and I value used in Unisim.

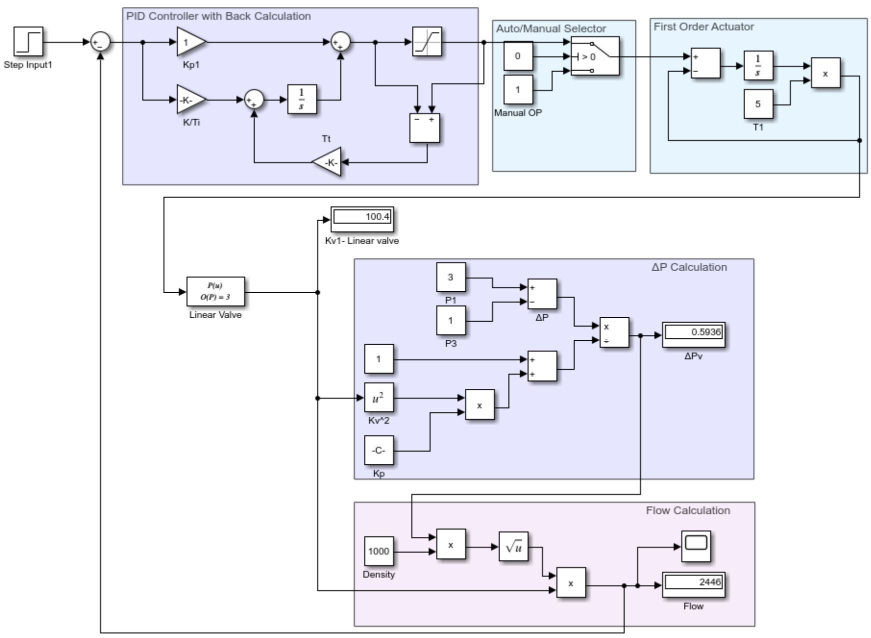


Figure 27: Closed loop implementation using a linear valve

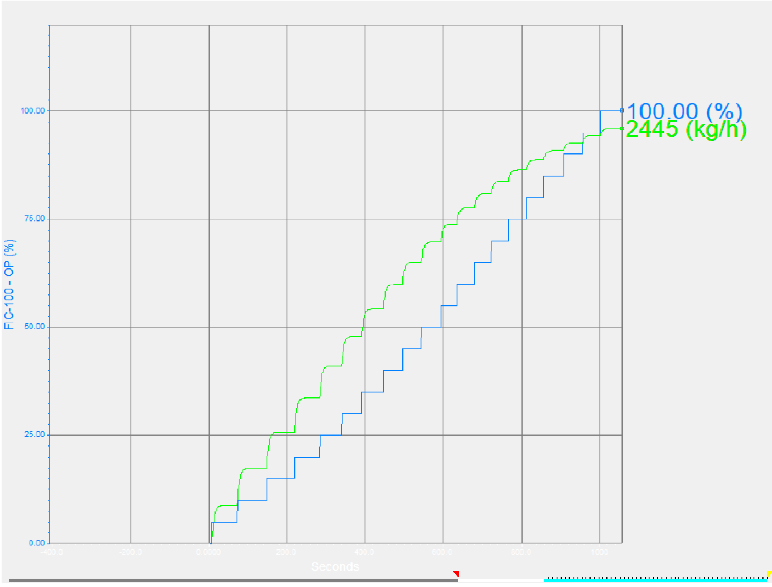


Figure 28: Linear valve step test - UniSim

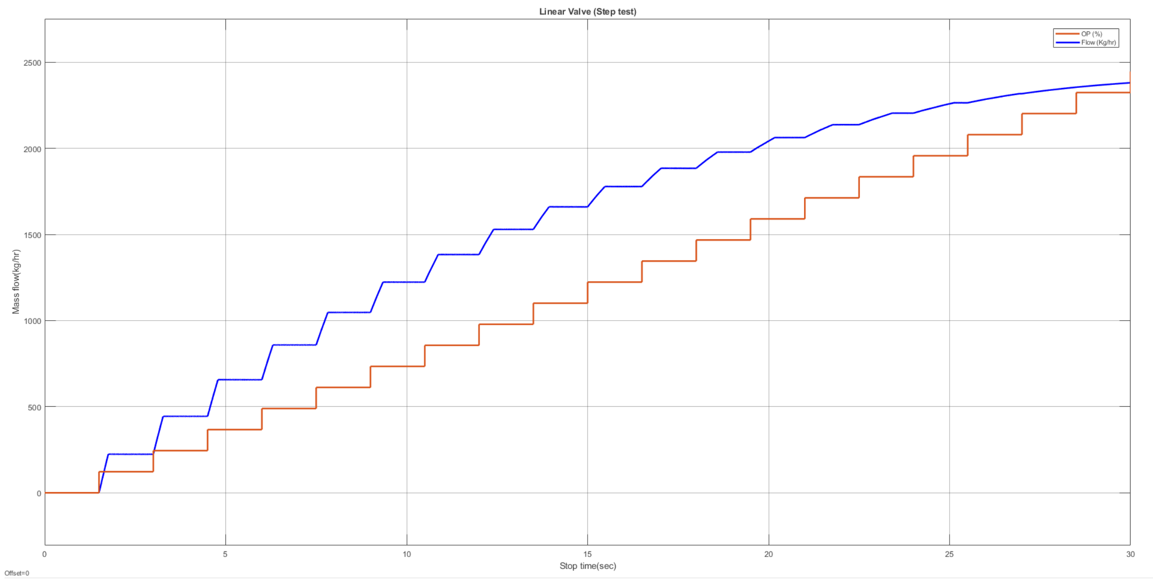


Figure 29: Linear valve step test - Simulink

As we can see, the figure 29 represents the behaviour of linear valve and there is some change in the behaviour from the ideal behaviour. This is true in the cases of differential pressure falling across the valve as the flow increases. Linear Valve comparison between UniSim and Simulink

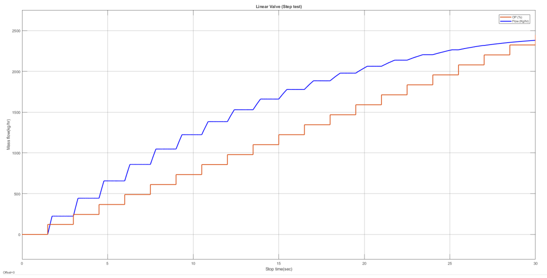
Unisim PV(kg/hr)	**OP(%)**	**p1**	**p2**	**p3**	**Delta Pp=p1-p2**	**Unisim -Delta Pv=p2-p3**	**Simulink Delta Pv=p2-p3**	**Y Calculated kv**	**Kp**
0	0	301.3	301.3	101.3	0	2	0	0	0
223.77	0.05	301.3	300.1	101.3	0.012	1.988	1.99	5.01872815	0.00023965
443.64	0.1	301.3	296.7	101.3	0.046	1.954	1.986	10.03617942	0.00023372
656.04	0.15	301.3	291.2	101.3	0.101	1.899	1.98	15.05455205	0.000234672
857.98	0.2	301.3	284	101.3	0.173	1.827	1.973	20.07279691	0.000235013
1047.3	0.25	301.3	275.5	101.3	0.258	1.742	1.963	25.09267884	0.000235222
1222.5	0.3	301.3	266.1	101.3	0.352	1.648	1.949	30.11412606	0.000235529
1383	0.35	301.3	256.3	101.3	0.45	1.55	1.93	35.12823513	0.000235271
1528.8	0.4	301.3	246.3	101.3	0.55	1.45	1.905	40.14825491	0.000235321
1660.3	0.45	301.3	236.4	101.3	0.649	1.351	1.871	45.17091557	0.000235435
1778.4	0.5	301.3	226.9	101.3	0.744	1.256	1.827	50.18045906	0.000235242
1884	0.55	301.3	217.8	101.3	0.835	1.165	1.768	55.19731287	0.000235247
1978.2	0.6	301.3	209.2	101.3	0.921	1.079	1.695	60.22259636	0.000235353
2062.3	0.65	301.3	201.2	101.3	1.001	0.999	1.6	65.24828449	0.000235359
2137.1	0.7	301.3	193.8	101.3	1.075	0.925	1.488	70.26741515	0.000235374
2203.8	0.75	301.3	187	101.3	1.143	0.857	1.358	75.28037395	0.000235343
2263.3	0.8	301.3	180.8	101.3	1.205	0.795	1.211	80.27097888	0.000235235
2316.5	0.85	301.3	175	101.3	1.263	0.737	1.052	85.32937421	0.000235363
2364	0.9	301.3	169.8	101.3	1.315	0.685	0.891	90.32379709	0.000235305
2406.6	0.95	301.3	165	101.3	1.363	0.637	0.7355	95.35296373	0.000235336
2444.9	1	301.3	160.6	101.3	1.407	0.593	0.5938	100.4000095	0.000235381

Table 4: Linear Valve comparison between UniSim and Simulink

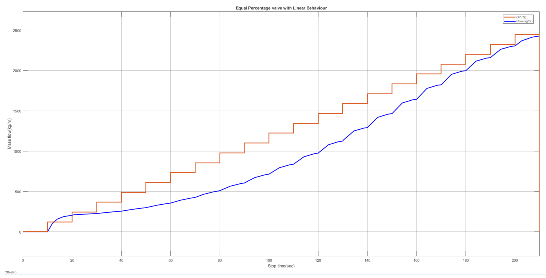
Unisim-PV(kg/hr)	**Simulink-PV(kg/hr)**	**Difference**
0	0	0
223.77	223.9	-0.13
443.64	443.9	-0.26
656.04	656.3	-0.26
857.98	858.2	-0.22
1047.3	1047	0.3
1222.5	1223	-0.5
1383	1383	0
1528.8	1529	-0.2
1660.3	1660	0.3
1778.4	1778	0.4
1884	1884	0
1978.2	1978	0.2
2062.3	2062	0.3
2137.1	2137	0.1
2203.8	2204	-0.2
2263.3	2264	-0.7
2316.5	2317	-0.5
2364	2365	-1
2406.6	2406	0.6
2444.9	2446	-1.1

Table 5: Linear Valve comparison between UniSim and simulink

8.3.2 Comparison between Linear and Equal percentage valve

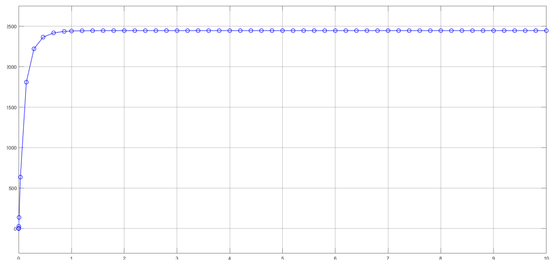


(a) Linear Valve Simulink

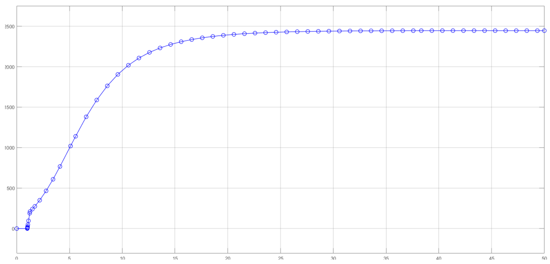


(b) Equal Percentage Step Test - Simulink

Figure 30: Comparison between Linear and equal percentage flow

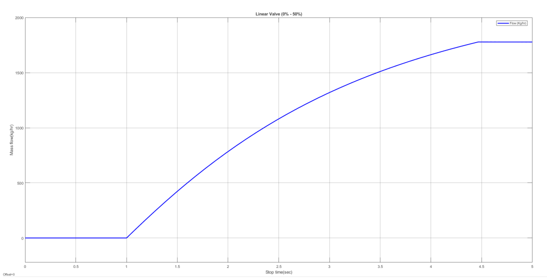


(a) Flow in Linear Valve

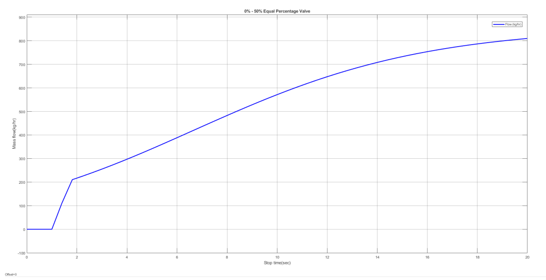


(b) Flow in Equal percentage valve

Figure 31: Comparison between Linear and equal percentage flow

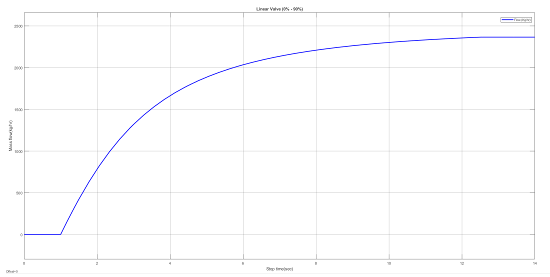


(a) 0-50 Simulink Linear valve

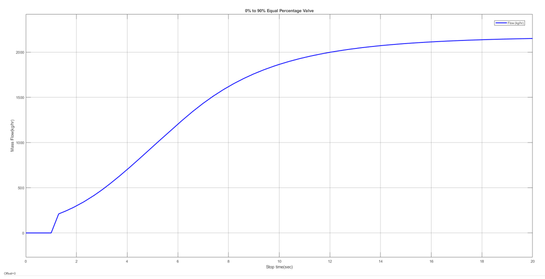


(b) 0-50 Simulink Equal percentage valve

Figure 32: Comparison between Linear and equal percentage flow in case of 0-50% of OP



(a) 0-90 Simulink Linear valve



(b) 0-90 Simulink Equal percentage valve

Figure 33: Comparison between Linear and equal percentage flow in case of 0-90% of OP

We can observe that the linear valve characteristics are a bit rounded rather than perfectly straight line, this is due to the differential pressure falling across the valve as the flow increases. In case the pump pressure had remained constant during the entire range of flow, the installation curve and the curve of the linear valve would have shown ideal behaviour, i.e. straight line.
While in case of equal percentage valve, although it is not linear throughout the whole travel, but it is above 50% flow rate.
In conclusion, the equal percentage valve offers an advantage over the linear valve at low flow rates.

9 Observations

- Non-linear relationship between the flow and pressure has been observed in the whole experimentation.
- The system behaves intact with the Anti-windup involvement in the PID controller.
- The linear valve settles faster than the equal percentage valve in higher OP ranges, and vice versa for lower OP ranges.
- Windup issues have been observed while developing PID controller by our own instead of taking built in model from Simulink library.
- Anti-windup can be developed by multiple ways, such as back calculation or by taking different type of controller like Override controller.

References

[1] Karl Johan Astrom and Tore Hagglund. *Advanced PID Control*. ISA, Research Triangle Park, June 2006.

[2] Using simulink -switch, 2008. URL http://matrix.etseq.urv.es/manuals/matlab/toolbox/simulink/ug/switch.html.

[3] Adolf H Glattfelder and Walther Schaufelberger. *Control systems with input and output constraints*. Advanced Textbooks in Control and Signal Processing. Springer, London, England, August 2003.

[4] Spiraxsarco. Control valve characteristics. https://www.spiraxsarco.com/learn-about-steam/control-hardware-electric-pneumatic-actuation/control-valve-characteristics/, 2010. [Online; Accessed 12 June 2022].