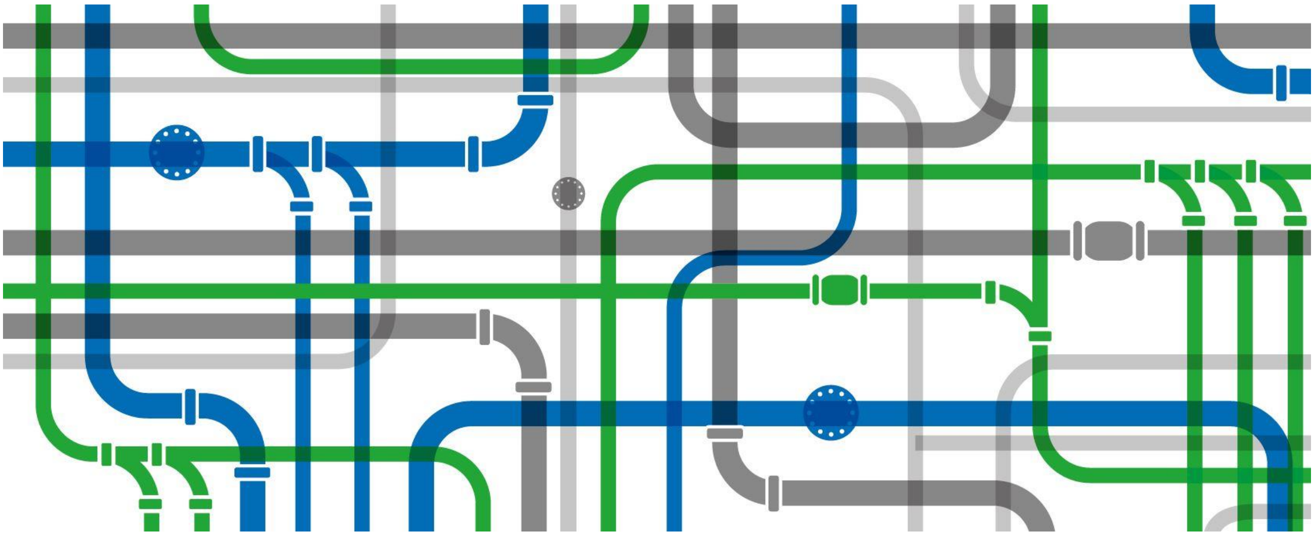
SLOT 2.0 User Manual



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Contents

Nomenclature

Symbol	Unit	Description
D	mm	internal pipe diameter
D_1	mm	internal pipe diameter on entry to fitting, e.g., expander
D_2	mm	internal pipe diameter on exit to fitting
f	-	Fanning friction factor
g	m/s^2	gravitational constant
h_{fitt}	m	head loss due to a pipe fitting
H	m	head of water or of slurry
He	-	Hedstrom number for Herschel-Bulkley or Bingham plastic model
k_{fitt}, k	-	loss coefficient for pipe fitting
k_1	-	parameter in Hooper's 2-K model
$\mathbf{k}_{\infty}$	-	parameter in Hooper's 2-K model
K	Pa s^n	consistency coefficient in Herschel-Bulkley model or power law model
L	m	pipe length, or thickness of orifice fitting
n	-	flow behaviour index in Herschel- Bulkley model or power law model
N	rpm	impeller speed of a rotodynamic pump
NPSHa	m	Net Positive Suction Head Available
$P_{startup}$	m	startup pressure (minimum frictional pressure differential across the system required for fluid motion to occur due to fluid static yield stress)
Q	litre/s	volumetric flowrate
Re_B	-	pipe Reynolds number for a Bingham plastic fluid
Re_{Bc}	-	critical Reynolds number; Bingham plastic fluid for laminar flow breakdown
Re_{HB}	-	pipe Reynolds number for a Herschel-Bulkley fluid
Re_{HBc}	-	critical Reynolds number; Herschel-Bulkley fluid for laminar flow breakdown
Re_N	-	pipe Reynolds number for a Newtonian fluid
Re_{Nc}	-	critical Reynolds number for Newtonian fluid for laminar flow breakdown
Re_{PL}	-	pipe Reynolds number for power law fluid
Re_{PLc}	-	critical Reynolds number for power law fluid for laminar flow breakdown
u^*	m/s	shear (or friction) velocity
$\bar{\mathbf{V}}$	m/s	mean fluid velocity in pipe
V_N	m/s	equivalent velocity of a Newtonian fluid in turbulent flow
x	-	ratio of yield stress parameter in a fluid model to the wall shear stress
z	m	elevation
β		parameter used in Wilson-Thomas turbulent flow models
$\dot{\boldsymbol{\gamma}}$	s^{-1}	shear rate
$\Delta P_{dynamic}$	Pa	pressure drop from changes in velocity
$\Delta P_{friction}$	Pa	pressure drop from friction
ΔP_{static}	Pa	pressure drop from changes in elevation
ΔP_{total}	Pa	sum of pressure losses from all contributions
ε	mm	inner pipe wall roughness (absolute value)
θ	degrees	angle of tapered expander, or reducer
μ	Pa s	viscosity of a Newtonian fluid
μ_{eff}	Pa s	effective fluid viscosity used in Wilson-Thomas turbulent flow models
μ_p	Pa s	plastic viscosity in the Bingham plastic model

ρ	kg/m^3	fluid density
τ	Pa	shear stress
τ_w	Pa	wall shear stress
τ_y	Pa	yield stress parameter in Herschel-Bulkley or Bingham plastic models
τ_0	Pa	static yield stress

1 Introduction

1.1 The Challenge

AMP7 requires Water Companies to optimise their existing facilities, providing “resilience in the round”. They also need to innovate, whilst providing great customer service and affordable bills.

The volume of sludge produced is increasing, with improved treatment solutions and the need to feed digesters creating greater amounts of green energy. Legislative restrictions on disposal will only become more onerous.

In addition, the nature of sludge is changing, with a drive to process ever thicker sludges to increase throughput, along with the introduction of new processes resulting in novel sludge types that have rheological properties that cannot be predicted using existing published rheology data.

This raises questions such as:

- How much energy is required to transport sludge within sludge treatment processes and beyond?
- What are the best pump, valve and pipeline solutions to move the sludge efficiently and in a resilient manner?
- Are current sludge systems operating at an optimal level? Are pumps undersized and overworked or oversized and underworked? Is the pipework too big?
- What do I need to ensure my existing or new system minimises its TOTEX costs over a fixed period or its lifetime and what is the impact?

1.2 What is SLOT 2.0?

SLOT 2.0 has been created to support organisations in meeting these challenges. It is a web-based software tool which has the most up-to-date calculation techniques embedded within it for determining the system pressure losses of a pipe network transporting a non-Newtonian (and/or Newtonian) fluid such as sewage sludge.

SLOT was initially developed as an Excel based tool during the WWM research programme run at BHR Group to update the outmoded TR185 based calculation methods. SLOT 2.0

takes the valuable work originally undertaken forward into an intuitive, easy to use software solution using Microsoft Azure.

1.3 What SLOT 2.0 does

SLOT 2.0 allows users to predict sludge rheological properties based on sludge type, dry solids content and temperature. Calculations are derived from the world's largest collection of rheograms. Users can:

- Quickly compare results for different fluid rheological properties and combinations of pumps, pipework and components, plotting system curves against pump curves to determine the operating points and enabling optimum pump selection.
- Plot fluid flow curves and the hydraulic grade line against the system elevation profile to check the feasibility of the pump operating points.

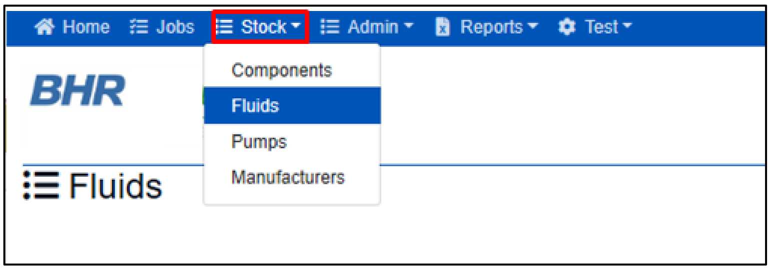
1.4 Accessing SLOT 2.0

The SLOT 2.0 software has been developed to operate on the latest versions of the Chrome and Safari web browsers. It can be accessed using the URL:
https://slot.framatomebhr.com/

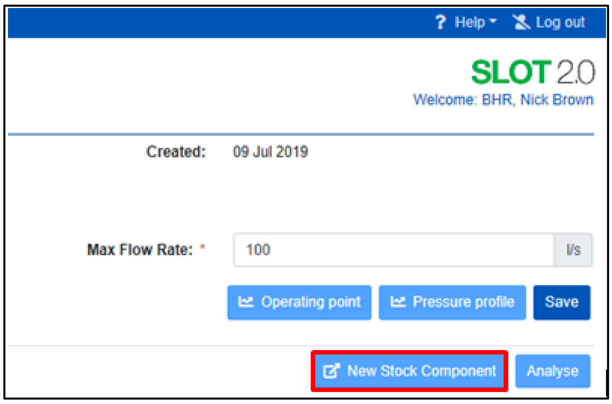
2 Building a Job

A Job is the name given in SLOT 2.0 for the combination of components, fluids and pumps involved in analysing the system losses of the pipe network and determining the pump operating point for the system. The Job requires the creation of Stock components, fluids and pumps which are then used within the Job to give a graphical comparison of the system loss curves and operating points for different fluids and pumps.

Stock items can be created using either the Stock tab:



or within the Job using the 'New Stock Component' button:



The following illustrates how a Job is created with an example network.

2.1 Stock Items

2.1.1 Fluid Creation:

To create a fluid click on the Stock – Fluids tab.

Create a Fluid using the button at the top right-hand-side of the screen.

- Note you may have to use the horizontal scroll bar at the bottom of the screen to be able to view the button, depending on your screen settings.

For example, create a Herschel-Bulkley non-Newtonian fluid using the 'Herschel-Bulkley coefficient picker', which uses data from the Sludge Rheology Database (SRDB):

- Name = Sludge-HB
- Description = Blank
- Notes = Sludge-HB SRDB input
- Shear Rate Min/Max = As default
- Density = 1200 kg/m^3
- Static Yield Stress = 0.5 Pa
- Rheological Model = Herschel-Bulkley
    - Temperature = 5°C
    - Confidence Limit = Mean
    - Category = Primary
    - Sub Category= Unthickened, No Fe
    - Dry Solids = 2.3%
    - Automatically fills in:
        - Description = Picker: 5˚C : Mean : Primary : Unthickened, No Fe : 2.3
        - Consistency Coefficient, K = 0.71
        - Yield Stress, τ_y = 0.14
        - Power Law Index, n = 0.45

2.1.2 Pump Creation:

Click on the Stock – Pumps tab.

Create a Pump using the  button:

- Name = Torishima Double-Suction
- Customer = Customer_Name
- Manufacturer = Torishima
    - Note if Manufacturer is not set up:
        - Specify ‘Unspecified’, complete steps below and save
        - Add new Manufacturer from Stock tab
        - Edit Pump to include new Manufacturer
- Type = Rotodynamic - Centrifugal
- Model = Double-Suction
- Rated Speed = 100 rpm
- Speed Min = 1 rpm
- Speed Max = 200 rpm
- Pump Curve:

Flow Rate (l/s)	Pressure (m.Fluid)
0	200
25	190
50	170
75	145
100	115

2.1.3 Component Creation:

Consider the following pipe system (bends: 90° standard & flanged, suction tank: outlet pipe flush & square-edged):

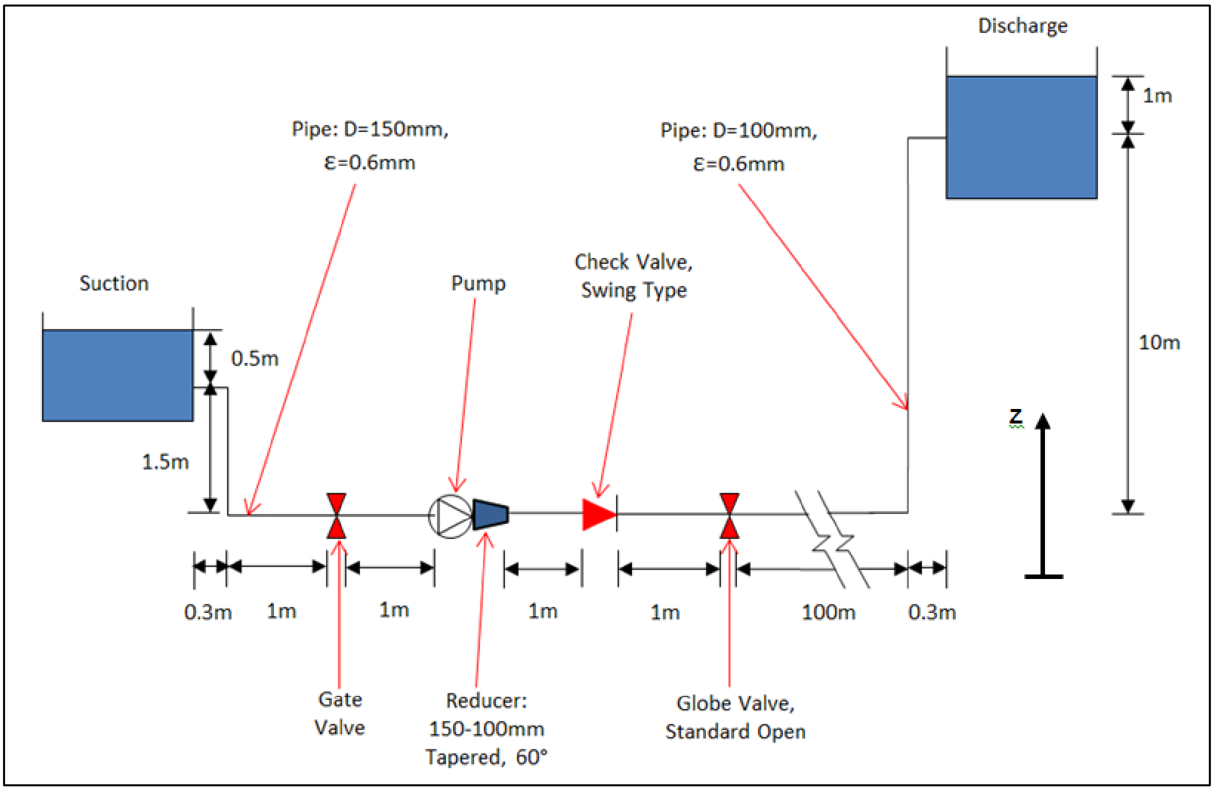


Figure 1 – Example Pipe Network

Click on the Stock – Components tab, and create a Component using the button:

Create a component for the suction tank:

- Name = Tank Suction (can add further identifiers to distinguish between other tanks in future)
- Manufacturer = None
- Customer = Customer_Name
- Type = Tank
- Position = Top (Suction = Top, Discharge = Bottom)
- Fitting Type = Flush, square-edged
- Outlet Diameter = 150 mm
- Head in tank = 0.5 m

Similarly create the following components (take care in naming the components so that you can easily find them again when assigning them to the Job; include dimension identifiers):

- Pipe; D=150 mm; ε=0.6 mm
    - Note pipe lengths & elevations are assigned within the Job – Component Item
    - D=pipe inner diameter, ε=pipe surface roughness (not used in laminar flow)
- Bend; D=150 mm; angle=90°; standard & flanged
- Valve; D=150 mm; Gate (open)
- Pump; D=150 mm, D2=150 mm, Head Added=0 m
    - The pump component here is a marker for the pump position to allow calculation of suction and discharge pressure; it doesn't use the pump curves defined in the Stock Pumps.
    - The Head Added can be included once the Operating Point is known to check the Pressure Profile for possible cavitation (see Section 2.3.3).
- Reducer; D=150 mm; D2=100 mm; Tapered; Angle=60°
- Pipe; D=100 mm; ε=0.6 mm
- Bend; D=100 mm; angle=90°; standard & flanged
- Valve; D=100 mm; Check; Swing Type
- Valve; D=100 mm; Globe; standard (open)
- Tank Bottom; D=100 mm; Head in tank = 1 m

2.2 Job Creation:

Click on the Jobs tab, and create a Job using the  button:

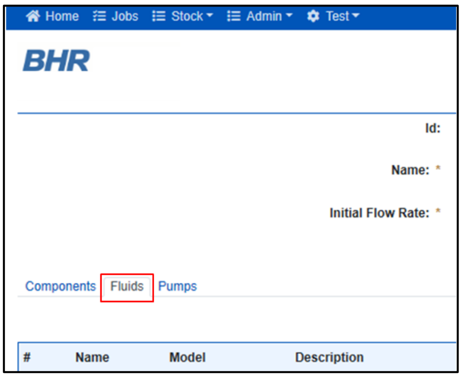
Create Job

- Name = Job_Name1
- Customer = Customer_Name
- Initial Flow Rate = 15 l/s
- Min Flow Rate = 0 l/s (for plotting purposes)
- Max Flow Rate = 100 l/s (for plotting purposes)

2.2.1 Fluid Assignment

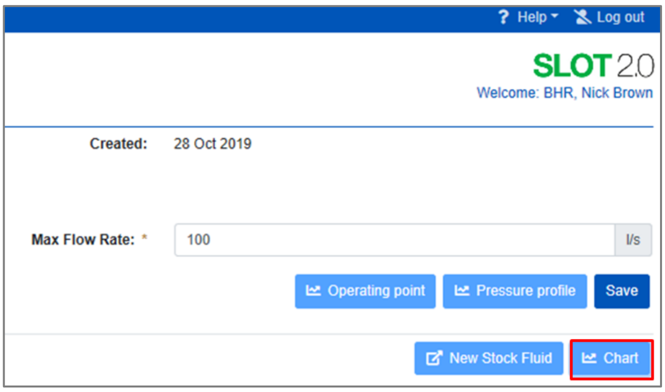
Assign Fluids to Job

- Within the Job select Fluids tab



- Assign a Fluid using the  button
- Select System defined Water fluid:
  - Rheological = Newtonian
  - Fluid = Water
- Select Customer defined ‘Sludge-HB’ fluid:
  - Rheological = Herschel-Bulkley
  - Fluid = Sludge-HB

The fluid flow curves can be plotted using the Chart button:



With Shear Stress vs Shear Rate (shown below) and Viscosity vs Shear Rate possible:

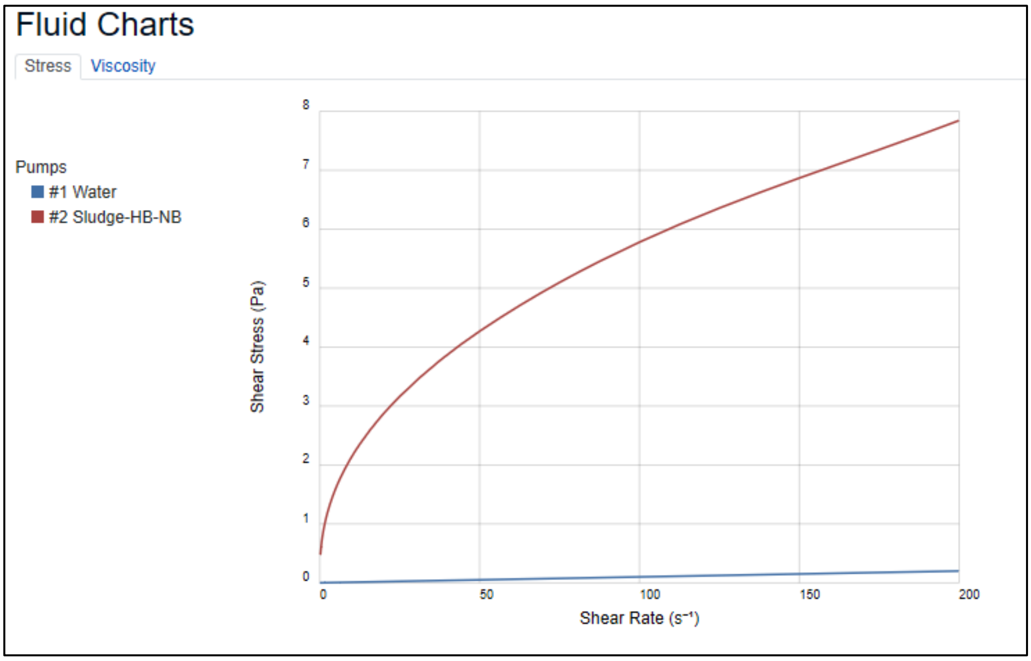


Figure 2 – Shear Stress vs Shear Rate Curve

2.2.2 Pump Assignment

Assign Pumps to Job

- Within the Job select Pumps tab
- Assign a Pump using the button
  - Select the Stock Pump created previously (must know Type):
    - Type = Rotodynamic – Centrifugal
    - Pump = Torishima Double-Suction
    - Speed = 100 rpm (same as Rated Speed)
    - Configuration = none
    - Save
- Assign a Pump using the button
  - Select the Stock Pump created previously as above, except:
    - Speed = 80 rpm (pump curve adapted according to Affinity Laws)
    - Save
- Assign a Pump using the button
  - Select the Stock Pump created previously as above, except:
    - Configuration = In Parallel
    - Number = 2
    - Save

2.2.3 Component Assignment

Assign Components to Job

- Within the Job select Components tab
- Assign a Component using the  button
    - Note if you make a mistake you can delete the row then use the Drag Row facility (see 2.4.1) to create a new component in the correct position.

1) Select the Stock item ‘Tank Suction’ created previously:
    - Type = Tank
    - Component = Tank Suction

- Similarly build the pipe network (see Figure 1), assigning the additional components:

2) Type=Pipe; Pipe D=150mm; Multiplier=1; Length=0.3 m; Change in Elevation* = 0 m
3) Type=Bend; Bend D=150mm; Multiplier=1
4) Type=Pipe; Pipe D=150mm; Multiplier=1; Length=1.5 m; Change in Elevation=-1.5 m
5) Type=Bend; Bend D=150mm; Multiplier=1
6) Type=Pipe; Pipe D=150mm; Multiplier=1; Length=1 m; Change in Elevation = 0 m
7) Type=Valve; Valve D=150mm Gate; Multiplier=1
8) Type=Pipe; Pipe D=150mm; Multiplier=1; Length=1 m; Change in Elevation = 0 m
9) Type=Pump; Pump D=150mm; Multiplier=1
10) Type=Reducer; Reducer 150 to 100mm Tapered; Multiplier=1
11) Type=Pipe; Pipe D=100mm; Multiplier=1; Length=1 m; Change in Elevation = 0 m
12) Type=Valve; Valve D=100mm Check Swing; Multiplier=1
13) Type=Pipe; Pipe D=100mm; Multiplier=1; Length=1 m; Change in Elevation = 0 m
14) Type=Valve; Valve D=100mm Globe Standard; Multiplier=1
15) Type=Pipe; Pipe D=100mm; Multiplier=1; Length=100 m; Change in Elevation = 0 m
16) Type=Bend; Bend D=100mm; Multiplier=1
17) Type=Pipe; Pipe D=100mm; Multiplier=1; Length=10 m; Change in Elevation = 10 m
18) Type=Bend; Bend D=100mm; Multiplier=1
19) Type=Pipe; Pipe D=100mm; Multiplier=1; Length=0.3 m; Change in Elevation = 0 m
20) Type=Tank; Tank Discharge

* Pipe elevation changes are specified relative to a coordinate frame that is positive in the vertically upward direction (see Figure 1). Elevation is specified relative to the previous component rather than to a reference datum.

2.3 Results

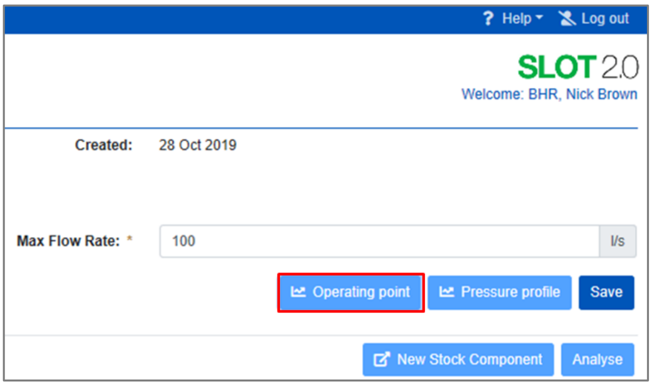
2.3.1 Analysis

Once components, fluids and pumps have been assigned to the Job, from within the Components tab, click the Analyse button. This opens a new window with a table of pressure losses for each component row (for the particular flow rate selected: 15 l/s):

							Pressure loss ΔP				Upstream pressure P					Downstream pressure P				
Type	V (m/s)	Re effective	Re down	Regime	ff	K	Friction (m.fluid)	Internal (m.fluid)	Potential (m.fluid)	Dynamic (m.fluid)	Total (m.fluid)	Internal (m.fluid)	Potential (m.fluid)	Piezo (m.fluid)	Dynamic (m.fluid)	Total (m.fluid)	Internal (m.fluid)	Potential (m.fluid)	Piezo (m.fluid)	Dynamic (m.fluid)
Tank	0.85	127324	127324	Turbulent	0.004279	0.501257	0.02	0.44	-0.50	0.04	0.50	0.00	0.50	0.50	0.00	0.48	0.44	0.00	0.44	0.04
Pipe	0.85	127324		Turbulent	0.007319	0.058555	0.00	0.00	0.00	0.00	0.48	0.44	0.00	0.44	0.04	0.48	0.44	0.00	0.44	0.04
Bend	0.85	127324		Turbulent	0.004279	0.298617	0.01	-0.01	0.00	0.00	0.48	0.44	0.00	0.44	0.04	0.47	0.43	0.00	0.43	0.04
Pipe	0.85	127324		Turbulent	0.007319	0.292773	0.01	1.49	-1.50	0.00	0.47	0.43	0.00	0.43	0.04	0.46	1.92	-1.50	0.42	0.04
Bend	0.85	127324		Turbulent	0.004279	0.298617	0.01	-0.01	0.00	0.00	0.46	1.92	-1.50	0.42	0.04	0.45	1.91	-1.50	0.41	0.04
Pipe	0.85	127324		Turbulent	0.007319	0.195182	0.01	-0.01	0.00	0.00	0.45	1.91	-1.50	0.41	0.04	0.44	1.90	-1.50	0.40	0.04
Valve	0.85	127324		Turbulent	0.004279	0.119290	0.00	0.00	0.00	0.00	0.44	1.90	-1.50	0.40	0.04	0.44	1.90	-1.50	0.40	0.04
Pipe	0.85	127324		Turbulent	0.007319	0.195182	0.01	-0.01	0.00	0.00	0.44	1.90	-1.50	0.40	0.04	0.43	1.89	-1.50	0.39	0.04
Pump	0.85	127324	127324	Turbulent	0.004279	0.000000	0.00	0.00	0.00	0.00	0.43	1.89	-1.50	0.39	0.04	0.43	1.89	-1.50	0.39	0.04
Reducer	0.85	127324	84883	Turbulent	0.004279	1.258594	0.05	-0.20	0.00	0.15	0.43	1.89	-1.50	0.39	0.04	0.38	1.70	-1.50	0.20	0.19
Pipe	1.91	190986		Turbulent	0.008140	0.325594	0.06	-0.06	0.00	0.00	0.38	1.70	-1.50	0.20	0.19	0.32	1.64	-1.50	0.14	0.19
Valve	1.91	190986		Turbulent	0.003945	1.888854	0.35	-0.35	0.00	0.00	0.32	1.64	-1.50	0.14	0.19	-0.03	1.28	-1.50	-0.22	0.19
Pipe	1.91	190986		Turbulent	0.008140	0.325594	0.06	-0.06	0.00	0.00	-0.03	1.28	-1.50	-0.22	0.19	-0.09	1.22	-1.50	-0.28	0.19
Valve	1.91	190986		Turbulent	0.003945	5.023854	0.93	-0.93	0.00	0.00	-0.09	1.22	-1.50	-0.28	0.19	-1.02	0.29	-1.50	-1.21	0.19
Pipe	1.91	190986		Turbulent	0.008140	32.559402	6.06	-6.06	0.00	0.00	-1.02	0.29	-1.50	-1.21	0.19	-7.08	-5.77	-1.50	-7.27	0.19
Bend	1.91	190986		Turbulent	0.003945	0.317689	0.06	-0.06	0.00	0.00	-7.08	-5.77	-1.50	-7.27	0.19	-7.14	-5.83	-1.50	-7.33	0.19
Pipe	1.91	190986		Turbulent	0.008140	3.255940	0.61	-10.61	10.00	0.00	-7.14	-5.83	-1.50	-7.33	0.19	-7.74	-16.43	8.50	-7.93	0.19
Bend	1.91	190986		Turbulent	0.003945	0.317689	0.06	-0.06	0.00	0.00	-7.74	-16.43	8.50	-7.93	0.19	-7.80	-16.49	8.50	-7.99	0.19
Pipe	1.91	190986		Turbulent	0.008140	0.097678	0.02	-0.02	0.00	0.00	-7.80	-16.49	8.50	-7.99	0.19	-7.82	-16.51	8.50	-8.01	0.19
Tank	1.91	190986		Turbulent	0.003945	1.000000	0.19	-1.00	1.00	-0.19	-7.82	-16.51	8.50	-8.01	0.19	-8.01	-17.51	9.50	-8.01	0.00

2.3.2 Operating Point

The system pressure loss curves are plotted along with the pump curves using the Operating point button, which again opens a new window:



The relevant Fluids for the system curves and Pumps for the pump curves can be selected using tick boxes on the top left hand side of the screen.

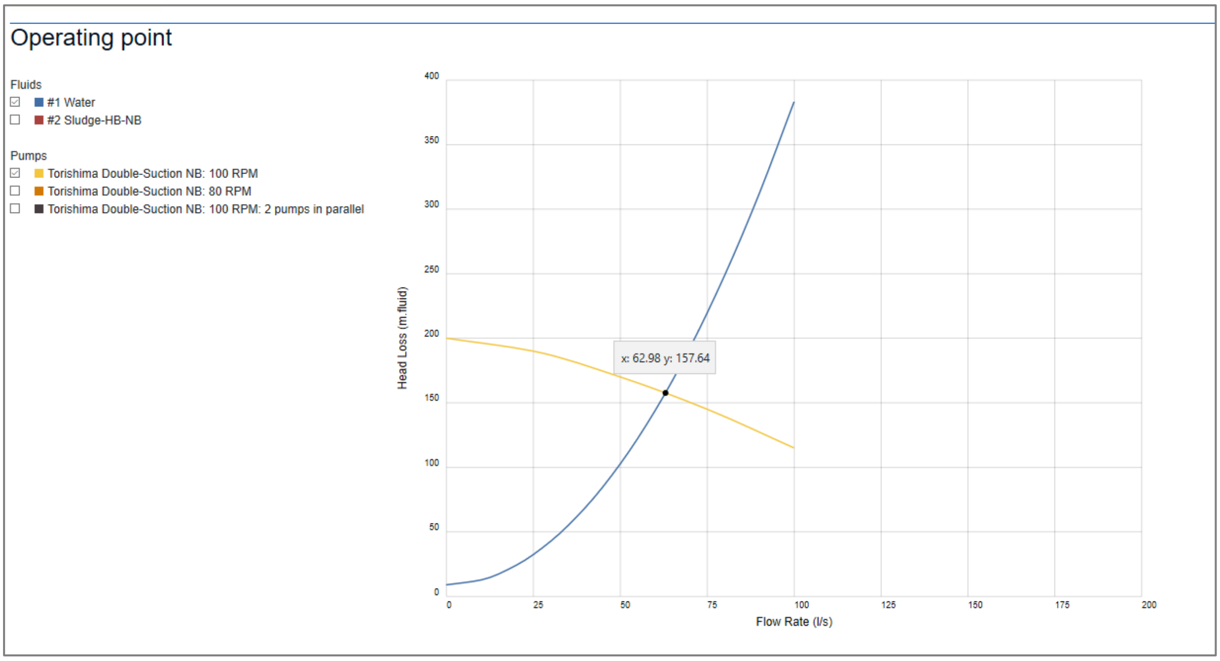


Figure 3 – Operating Point Curve

Hovering the cursor over the intersection point shows the precise operating point: for the network of components selected with Water and the Torishima Double-Suction pump at 100 rpm the operating point is Flow Rate = 62.98 l/s, Head Loss = 157.64 m.

Adding all fluids and pumps shows how the operating point varies with changes in:

- Fluid: Herschel-Bulkley sludge compared to water.
- Pump: changing the pump speed and configuration (2 in parallel).

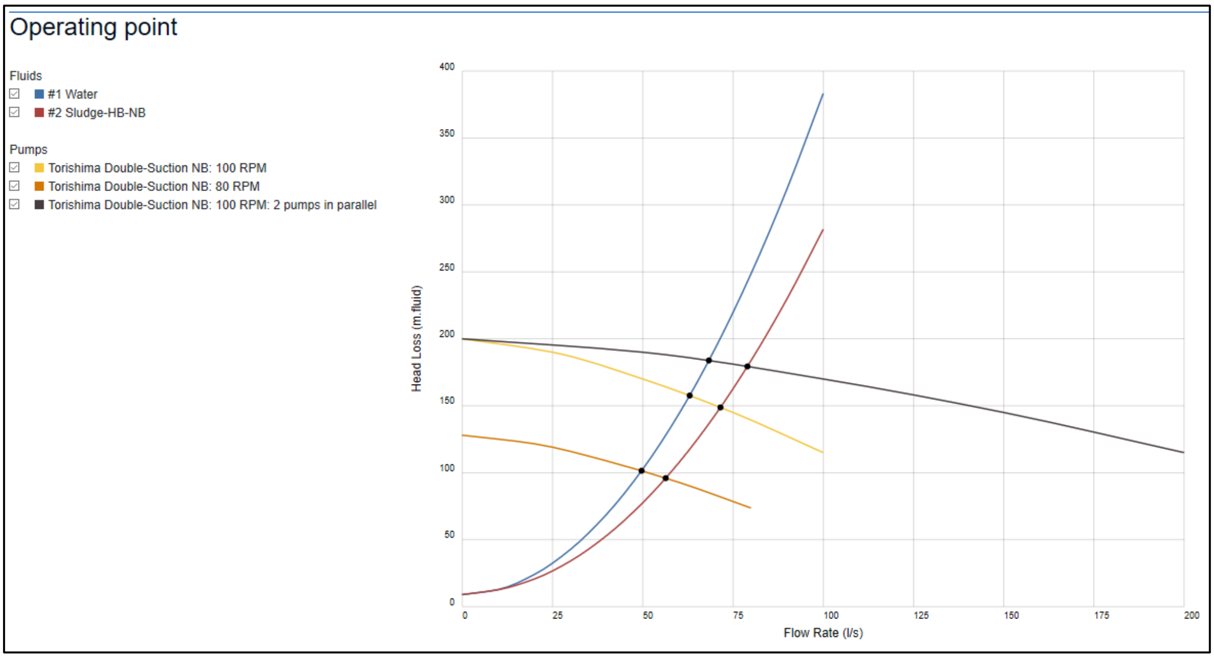


Figure 4 – Multiple Operating Points

2.3.3 Pressure Profile

Examining the Pressure Profile corresponding to the operating point for Water and the Torishima Double-Suction pump at 100 rpm (Q = 62.98 l/s, H = 157.64 m), go back to edit the Job:

- Change the flow rate to 62.98 l/s.
- Edit the pump within the Stock Components (Pump D=150mm)
    - Change Head Added to 157.64 m
- Click the 'Analyse' button
- Click the 'Pressure Profile' button:

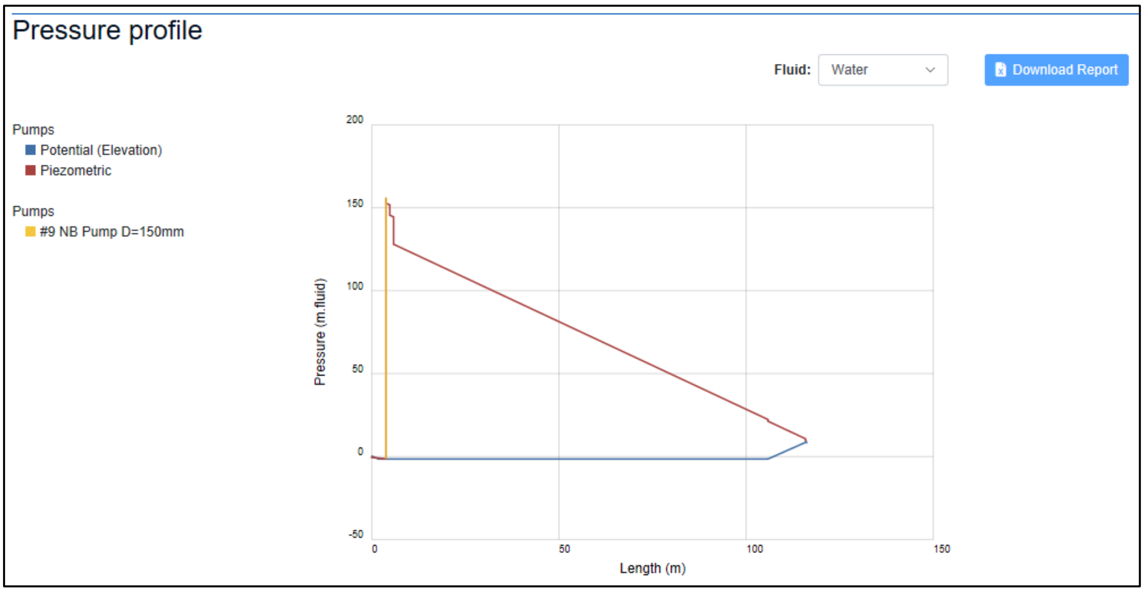


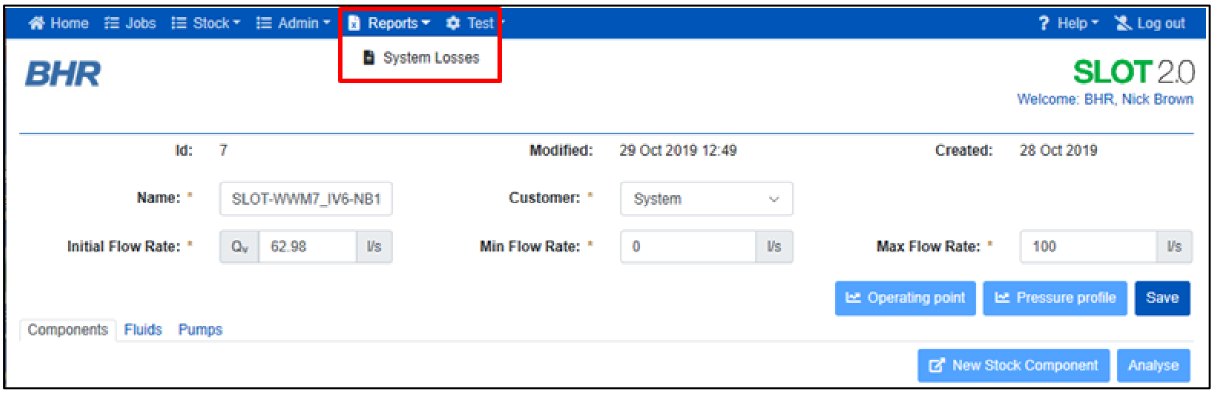
Figure 5 – Pressure Profile Graph

So as expected the piezometric pressure/head matches the head due to elevation at the discharge point, and we can see that in this case the piezometric head is always above the elevation so there is no risk of cavitation (at least in the steady-state case considered).

The data underlying the Pressure Profile graph can be exported to Excel format using the ‘Download Report’ button.

2.3.4 Report Export

Once the ‘Analyse’ button has been clicked on the Job the ‘System Losses’ report becomes available in the Reports tab:



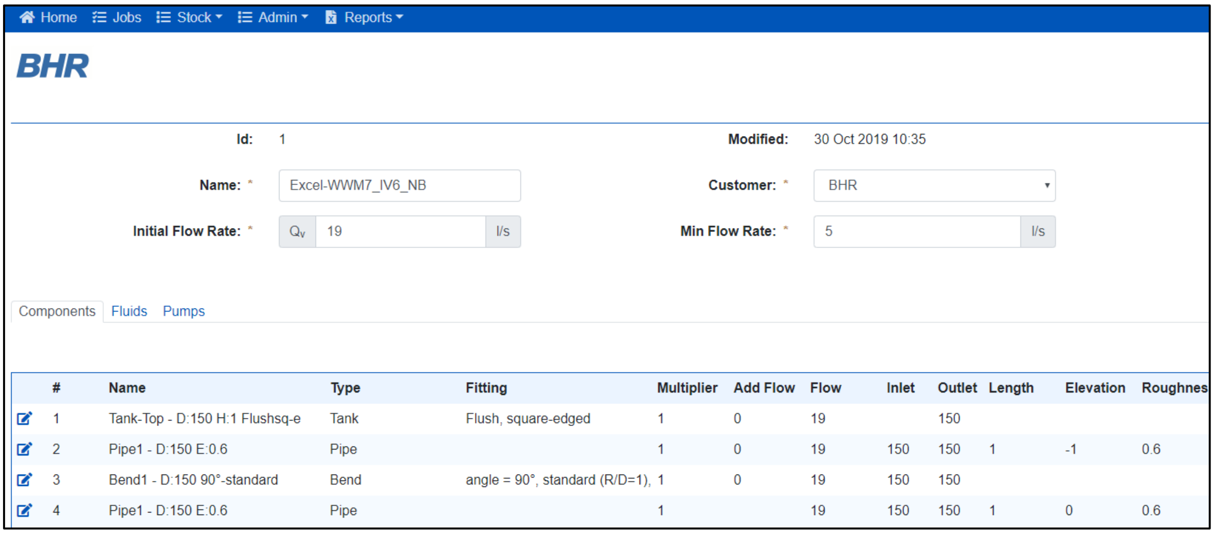
In this report (see Data tab) you can find the following summary data behind Job calculations, including:

- $\Delta P_{friction}$ = frictional pressure losses
- ΔP_{static} = ΔP from changes in elevation
- $\Delta P_{dynamic}$ = ΔP from changes in velocity
- ΔP_{total} = sum of ΔP from above contributions
- ΔP on Suction and Discharge sides of the pump
- NPSHa = Net Positive Suction Head Available
- $P_{startup}$ = pressure required to overcome fluid static shear stress
- Summary of fluid data
- Summary of Max/min component diameters, Reynolds numbers and corresponding regimes
- Summary of pump data

2.4 Further Capabilities

2.4.1 Drag Rows (Components)

Within the Job – Components dialogue:



It is possible to reorder the component rows by clicking on a row and dragging it to the required position. In this way mistakes can be corrected, *e.g.* by deleting a row, creating a new component row at the end, and then using the Drag Row facility to move it to the correct position.

2.4.2 Multiplier

When assigning a Component to a Job there is a Multiplier functionality designed for use when the same fitting (same type, dimensions, etc.) is used multiple times. Care should be taken to only use this for components situated at the same elevation or the ΔP_{static} won't be accounted for correctly and the Pressure Profile will be wrong.

2.5 Case Study 2

A second case study is presented below:

2.5.1 Network Components

ID	Type	Component Parameters	Length [m]	Elevation [m]	Multiplier	Added Flow [l/s]
1	Tank	Top; Flush, square-edged; Dout=150mm; Head=0.5m	N/A	N/A	1	N/A
2	Pipe	D=150 mm; ε=0.6 mm	0.3	0	1	N/A
3	Bend	D=150 mm; angle=90°; standard & flanged	N/A	N/A	1	N/A
4	Pipe	D=150 mm; ε=0.6 mm	1.5	-1.5	1	N/A
5	Bend	D=150 mm; angle=90°; standard & flanged	N/A	N/A	1	N/A
6	Pipe	D=150 mm; ε=0.6 mm	1	0	1	N/A
7	Valve	D=150 mm; Gate (open)	N/A	N/A	1	N/A
8	Pipe	D=150 mm; ε=0.6 mm	1	0	1	N/A
9	Pump	D=150 mm; D2=150 mm; Head Added=0 m	N/A	N/A	1	N/A
10	Reducer	D=150 mm; D2=100 mm; Tapered; Angle=60°	N/A	N/A	1	N/A
11	Pipe	D=100 mm; ε=0.6 mm	1	0	1	N/A
12	Valve	D=100 mm; Check; Swing Type	N/A	N/A	1	N/A
13	Pipe	D=100 mm; ε=0.6 mm	1	0	1	N/A
14	Valve	D=100 mm; Globe; standard (open)	N/A	N/A	1	N/A
15	Pipe	D=100 mm; ε=0.6 mm	100	0	1	N/A
16	Tee	D=100 mm; used as elbow, standard	N/A	N/A	1	5
17	Pipe	D=100 mm; ε=0.6 mm	100	0	1	N/A
18	Valve	D=100 mm; Diaphragm	N/A	N/A	1	N/A
19	Pipe	D=100 mm; ε=0.6 mm	100	0	1	N/A
20	Valve	D=100 mm; Butterfly	N/A	N/A	1	N/A
21	Pipe	D=100 mm; ε=0.6 mm	100	0	1	N/A
22	Expander	D=100 mm; Dout=150mm; Sudden	N/A	N/A	1	N/A
23	Reducer	D =150 mm; Dout=100mm; Sudden	N/A	N/A	1	N/A
24	Expander	D=100 mm; Dout=150mm; Rounded	N/A	N/A	1	N/A
25	Pipe	D=150 mm; ε=0.6 mm	1	0	1	N/A
26	Orifice	D=150 mm; Dinternal=50; Thin & Sharp	N/A	N/A	1	N/A
27	Pipe	D=150 mm; ε=0.6 mm	1	0	1	N/A

28	Orifice	D=150 mm; Dinternal=50; Thick; L=50mm	N/A	N/A	1	N/A
29	Pipe	D=150 mm; ε=0.6 mm	1	0	1	N/A
30	User Defined	D =150 mm; Dout=100mm; K=1.5	N/A	N/A	1	N/A
31	Pipe	D=100 mm; ε=0.6 mm	100	0	1	N/A
32	Bend	D=100 mm; angle=45°; standard	N/A	N/A	1	N/A
33	Pipe	D=100 mm; ε=0.6 mm	100	0	1	N/A
34	Bend	D=100 mm; angle=45°; long radius	N/A	N/A	1	N/A
35	Pipe	D=100 mm; ε=0.6 mm	100	0	1	N/A
36	Bend	D=100 mm; angle=90°; elbow	N/A	N/A	1	N/A
37	Pipe	D=100 mm; ε=0.6 mm	100	0	1	N/A
38	Bend	D=100 mm; angle=90°; standard, threaded	N/A	N/A	1	N/A
39	Pipe	D=100 mm; ε=0.6 mm	100	0	1	N/A
40	Bend	D=100 mm; angle=90°; long radius	N/A	N/A	1	N/A
41	Pipe	D=100 mm; ε=0.6 mm	100	0	1	N/A
42	Bend	D=100 mm; angle=180°; flanged	N/A	N/A	1	N/A
43	Pipe	D=100 mm; ε=0.6 mm	100	0	1	N/A
44	Bend	D=100 mm; angle=180°; standard, threaded	N/A	N/A	1	N/A
45	Tee	D=100 mm; run through, threaded	N/A	N/A	1	-5
46	Bend	D=100 mm; angle=90°; standard & flanged	N/A	N/A	1	N/A
47	Pipe	D=100 mm; ε=0.6 mm	10	10	1	N/A
48	Bend	D=100 mm; angle=90°; standard & flanged	N/A	N/A	1	N/A
49	Pipe	D=100 mm; ε=0.6 mm	0.3	0	1	N/A
50	Tank	Bottom; D=100 mm; Head in tank = 1 m	N/A	N/A	1	N/A

2.5.2 Fluids

Fluid 1, Density=1200 kg/m³, Min/Max Shear Rate as default, Static Yield Stress=0 Pa, Power Law, K=0.1, n=0.5.

Fluid 2, Density=1050 kg/m³, Min/Max Shear Rate as default, Static Yield Stress=0 Pa, Bingham Plastic, K=0.2, τ_y=0.5.

2.5.3 Pumps

Create Stock Pump:

- Name = Kubota Axial
- Customer = Customer_Name
- Manufacturer = Kubota
- Type = Rotodynamic - Axial
- Model = Axial
- Rated Speed = 200 rpm
- Speed Min = 1 rpm
- Speed Max = 400 rpm
- Pump Curve:

Flow Rate (l/s)	Pressure (m.Fluid)
0	400
50	360
100	315
150	270
200	215

Jobs – Pumps

1) Select Kubota Axial pump, with Speed = 200 rpm, Configuration = None
2) Select Kubota Axial pump, with Speed = 200 rpm, Configuration = In Series, Number=2

Job Parameters:

- Initial Flow Rate = 65 l/s
- Min Flow Rate = 0 l/s
- Max Flow Rate = 100 l/s

Change Max Flow Rate to enable intersection of curves in Operating Point graph.

3 Model Elements

A detailed summary of all the model variables is presented in this section.

3.1 Stock Items

To create a Job you must first create the Stock Items to assign to the Job. The different Stock items are Fluids, Pumps and Components, which can be created either from the Stock tab at the top of the main page or from the New Stock buttons within the actual Job page. The following variables must be input/selected when creating a new Stock Item via the appropriate dialogue page:

3.1.1 Fluids

The 'Stock Fluid Item' page includes the following input variables and options:

Input Parameter	Option 1	Option 2	Option 3
Name *	Text, to be created		
Customer *	Automatically selected		
Description *	Text, to be created		
Notes	Text, to be created		
Shear Rate Min, γ [s^{-1}] *	Number (0 to 2000)		
Shear Rate Max, γ [s^{-1}] *	Number (1 to 2000)		
Density, ρ [kg/m^3] *	Number (900 to 1600)		
Static Yield Stress, τ_0 [Pa] [1] *	Number (0 to 500)		
Rheological Model *	Bingham Plastic	Consistency Coefficient, K [Pa.s] *****	Number (0.01 to 1000)
		Yield Stress, τ_y [Pa] *****	Number (0 to 500)
	Herschel-Bulkley [2]	Consistency Coefficient, K [$Pa.s^n$] *****	Number (0.01 to 1000)
		Yield Stress, τ_y [Pa] *****	Number (0 to 500)
		Power Law Index, n *****	Number (0.1 to 0.98)
	Newtonian	Dynamic Viscosity, μ [Pa.s] *****	Number (0.0005 to 10)
	Power Law	Consistency Coefficient, K [$Pa.s^n$] *****	Number (0.01 to 1000)
		Power Law Index, n *****	Number (0.1 to 0.98)

* Compulsory field, same for all in Section 3. Warning message will appear if left blank.

[1] The Static Yield Stress, which defines the minimum shear stress which must be exceeded for fluid motion to occur, is only used in the Pump Startup Pressure calculation (see Section 5.5). The default value is set to zero. This is not the same as the Yield Stress, τ_y, which is a curve fitting parameter to the experimental rheological data.

[2] If the Herschel-Bulkley Rheological Model is selected the Herschel-Bulkley coefficient picker tool appears, which uses the Sludge Rheology Database (SRDB) developed by Framatome BHR (see Section 5.2.2) to automatically select the Herschel-Bulkley flow curve parameters based on the following sewage sludge characteristic values:

<table>
<tr><th>Input Parameter</th><th>Option 1</th><th>Option 2</th><th>Option 3</th></tr>
<tr><td>Temperature [°C] *</td><td colspan="3">Number (5 to 85)</td></tr>
<tr><td rowspan="3">Confidence Limit [1] *</td><td colspan="3">95% Confidence Max</td></tr>
<tr><td colspan="3">95% Confidence Min</td></tr>
<tr><td colspan="3">Mean</td></tr>
<tr><td rowspan="18">Category [2] *</td><td rowspan="2">Blended</td><td rowspan="2">Sub Category *</td><td>Thickened</td></tr>
<tr><td>Unthickened</td></tr>
<tr><td rowspan="3">Digested</td><td rowspan="3">Sub Category *</td><td>Cambi</td></tr>
<tr><td>Thickened</td></tr>
<tr><td>Unthickened</td></tr>
<tr><td rowspan="3">Hydrolysed</td><td rowspan="3">Sub Category *</td><td>Alpha</td></tr>
<tr><td>Cambi</td></tr>
<tr><td>EH</td></tr>
<tr><td>Potable</td><td>Sub Category *</td><td>Poly & Fe dosed</td></tr>
<tr><td rowspan="4">Primary</td><td rowspan="4">Sub Category *</td><td>Thickened, Belt</td></tr>
<tr><td>Thickened, Drum & Gravity</td></tr>
<tr><td>Unthickened, Fe dosed</td></tr>
<tr><td>Unthickened, No Fe</td></tr>
<tr><td rowspan="3">Secondary</td><td rowspan="3">Sub Category *</td><td>Thickened, Belt, no Coag</td></tr>
<tr><td>Thickened, Belt, with Coag</td></tr>
<tr><td>Thickened, Gravity & Drum</td></tr>
<tr><td>Dry Solids [%] *</td><td colspan="3">Discrete numerical value to be selected, allowable range depends on category chosen</td></tr>
</table>

[1] Note that it is a Prediction Limit rather than a Confidence Limit implemented in the SRDB Correlation Calculator (see Section 5.2.2).

[2] Refer to Table 1.

3.1.2 Pumps

The 'Stock Pump Item' page includes the following input variables and options:

Input Parameter	Options
Name *	Text, to be created
Customer *	Automatically selected
Manufacturer *	Select what has been created
Type *	Positive Displacement - Gear
	Positive Displacement - Lobe
	Positive Displacement - Peristaltic
	Positive Displacement - Progressive Cavity
	Positive Displacement - Reciprocating
	Positive Displacement - Screw
	Positive Displacement - Vane
	Rotodynamic - Axial
	Rotodynamic - Centrifugal
	Rotodynamic - Mixed Flow
	Unspecified
Model	Text, to be created
Rated Speed [rpm] *	Number (1 to 1000)
Speed Min [rpm] *	Number (1 to 1000)
Speed Max [rpm] *	Number (1 to 1000)
Flow Rate [l/s] *	Number (0 to 10000; input Pump Curve data, must provide at least 2 values)
Pressure [m.fluid] *	Number (0 to 10000; input Pump Curve data, must provide at least 2 values)

3.1.3 Components

The ‘Stock Component Item’ page includes the following input variables and options:

<table>
<tr><th>Input Parameter</th><th>Options 1</th><th>Options 2</th><th>Options 3</th><th>Options 4</th><th>Options 5</th></tr>
<tr><td>Name *</td><td colspan="5">Text, to be created (choose name carefully to be able to find among the list of created components when assigning to the Job; include fitting type, dimensions, etc.)</td></tr>
<tr><td>Manufacturer *</td><td colspan="5">Select what has been created</td></tr>
<tr><td>Customer *</td><td colspan="5">Automatically selected</td></tr>
<tr><td rowspan="18">Type *</td><td rowspan="9">Bend (see Table 3)</td><td>Internal Diameter, D [mm] *</td><td colspan="3">Number (1 to 10000)</td></tr>
<tr><td rowspan="8">Fitting Type *</td><td rowspan="2">Angle=45°</td><td rowspan="2">Fitting Use *</td><td>standard (R/D=1)</td></tr>
<tr><td>long radius (R/D=1.5)</td></tr>
<tr><td rowspan="4">Angle=90°</td><td rowspan="4">Fitting Use *</td><td>elbow</td></tr>
<tr><td>standard (R/D=1), flanged or welded</td></tr>
<tr><td>standard (R/D=1), threaded</td></tr>
<tr><td>long radius (R/D=1.5)</td></tr>
<tr><td rowspan="2">Angle=180°</td><td rowspan="2">Fitting Use *</td><td>standard (R/D=1), flanged or welded</td></tr>
<tr><td>standard (R/D=1), threaded</td></tr>
<tr><td rowspan="5">Expander (see Table 6)</td><td>Inlet Diameter, D [mm] *</td><td colspan="3">Number (1 to 10000)</td></tr>
<tr><td>Outlet Diameter, D_2 [mm] *</td><td colspan="3">Number (1 to 10000)</td></tr>
<tr><td rowspan="3">Fitting Type *</td><td colspan="3">Rounded</td></tr>
<tr><td colspan="3">Sudden (abrupt)</td></tr>
<tr><td>Tapered</td><td>Angle, α [deg] *</td><td>Number (0.1 to 179.9)</td></tr>
<tr><td rowspan="4">Orifice (see Table 6)</td><td>Diameter, D [mm] *</td><td colspan="3">Number (1 to 10000)</td></tr>
<tr><td>Internal Diameter, D_2 [mm] *</td><td colspan="3">Number (1 to 10000)</td></tr>
<tr><td rowspan="2">Fitting Type *</td><td>Thick</td><td>Thickness, L_0 [mm] *</td><td>Number (1 to 100)</td></tr>
<tr><td colspan="3">Thin & sharp</td></tr>
</table>

‘Type’ continued:

<table>
<tr><th>Options 1</th><th>Options 2</th><th>Options 3</th><th>Options 4</th><th>Options 5</th><th>Options 6</th></tr>
<tr><td rowspan="2">Pipe</td><td>Internal Diameter, D [mm]*</td><td colspan="4">Number (1 to 10000)</td></tr>
<tr><td>Roughness, ε [mm] * (Absolute)</td><td colspan="4">Number (0.001 to 10; see representative values in Table 2)</td></tr>
<tr><td rowspan="3">Pump</td><td>Inlet Diameter, D [mm] *</td><td colspan="4">Number (1 to 10000)</td></tr>
<tr><td>Outlet Diameter, D_2 [mm] *</td><td colspan="4">Number (1 to 10000)</td></tr>
<tr><td>Head Added, ΔP [m.fluid] *</td><td colspan="4">Number (0 to 1000)</td></tr>
<tr><td rowspan="5">Reducer (see Table 6)</td><td>Inlet Diameter, D [mm] *</td><td colspan="4">Number (1 to 10000)</td></tr>
<tr><td>Outlet Diameter, D_2 [mm] *</td><td colspan="4">Number (1 to 10000)</td></tr>
<tr><td rowspan="3">Fitting Type *</td><td colspan="4">Rounded</td></tr>
<tr><td colspan="4">Sudden (abrupt)</td></tr>
<tr><td>Tapered</td><td>Angle, α [deg] *</td><td colspan="2">Number (0.1 to 179.9)</td></tr>
<tr><td rowspan="11">Tank (see Table 4 & Table 5)</td><td rowspan="11">Position *</td><td rowspan="2">Downstream</td><td>Inlet Diameter, D [mm] *</td><td colspan="2">Number (1 to 10000)</td></tr>
<tr><td>Head in tank (above pipe), H_t [m] *</td><td colspan="2">Number (0 to 1000)</td></tr>
<tr><td rowspan="9">Upstream</td><td rowspan="7">Fitting Type *</td><td colspan="2">Flush, square-edged</td></tr>
<tr><td colspan="2">Inward-projecting (Borda)</td></tr>
<tr><td rowspan="5">Rounded</td><td>r/D = 0.02</td></tr>
<tr><td>r/D = 0.04</td></tr>
<tr><td>r/D = 0.06</td></tr>
<tr><td>r/D = 0.10</td></tr>
<tr><td>r/D >= 0.15</td></tr>
<tr><td>Outlet Diameter, D [mm] *</td><td colspan="2">Number (1 to 10000)</td></tr>
<tr><td>Head in tank (above pipe), H_t [m] *</td><td colspan="2">Number (0 to 1000)</td></tr>
<tr><td rowspan="5">Tee (see Table 3)</td><td>Internal Diameter, D [mm]*</td><td colspan="4">Number (1 to 10000)</td></tr>
<tr><td rowspan="4">Fitting Type *</td><td rowspan="2">run through (side blocked)</td><td rowspan="2">Fitting Use *</td><td colspan="2">flanged or welded</td></tr>
<tr><td colspan="2">threaded</td></tr>
<tr><td rowspan="2">used as elbow</td><td rowspan="2">Fitting Use *</td><td colspan="2">long radius</td></tr>
<tr><td colspan="2">standard</td></tr>
<tr><td rowspan="3">User Defined</td><td>Inlet Diameter, D [mm] *</td><td colspan="4">Number (1 to 10000)</td></tr>
<tr><td>Outlet Diameter, D_2 [mm] *</td><td colspan="4">Number (1 to 10000)</td></tr>
<tr><td>Loss Coefficient, K [] *</td><td colspan="4">Number (0 to 100; K constant, only appropriate for turbulent flow)</td></tr>
</table>

Type' continued:

<table>
<tr><th>Options 1</th><th>Options 2</th><th>Options 3</th><th>Options 4</th><th>Options 5</th></tr>
<tr><td rowspan="9">Valve
(see
Table 3)</td><td>Internal Diameter, D mm] *</td><td colspan="3">Number (1 to 10000)</td></tr>
<tr><td rowspan="8">Fitting Type *</td><td colspan="3">Butterfly</td></tr>
<tr><td rowspan="3">Check</td><td rowspan="3">Fitting Use *</td><td>lift type</td></tr>
<tr><td>swing type</td></tr>
<tr><td>tilting type</td></tr>
<tr><td>Diaphragm</td><td>Fitting Use *</td><td>dam-type (open)</td></tr>
<tr><td>Gate (open)</td><td>Fitting Use *</td><td>N/A</td></tr>
<tr><td rowspan="2">Globe</td><td rowspan="2">Fitting Use *</td><td>angle or Y-type (open)</td></tr>
<tr><td>standard (open)</td></tr>
</table>

3.2 Job Page

When adding a new job the Overall Job Page includes the following input variables:

Input Parameter	Options
Name *	Text, to be created
Customer *	Automatically selected
Initial Flow Rate, Q_v [l/s] *	Number (0 to 1000)
Min Flow Rate [l/s] *	Number (0 to 1000; used in plotting limits for Operating Point graphs)
Max Flow Rate [l/s] *	Number (0 to 1000; used in plotting limits for Operating Point graphs)

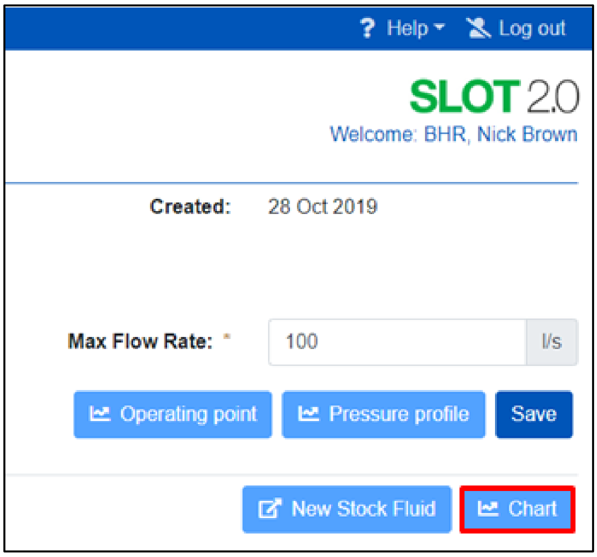
3.2.1 Fluid

When assigning a fluid to the Job the 'Fluid Item' page features the following options to be selected:

<table>
<tr><th>Input Parameter</th><th>Options</th></tr>
<tr><td rowspan="4">Rheological Model *</td><td>Bingham Plastic</td></tr>
<tr><td>Herschel-Bulkley</td></tr>
<tr><td>Newtonian</td></tr>
<tr><td>Power Law</td></tr>
<tr><td>Fluid *</td><td>Select fluid 'Name' already created</td></tr>
</table>

a) Chart

When at least one fluid has been entered into the Job the Chart button can be accessed:



The Chart button outputs plots of shear stress against shear rate:

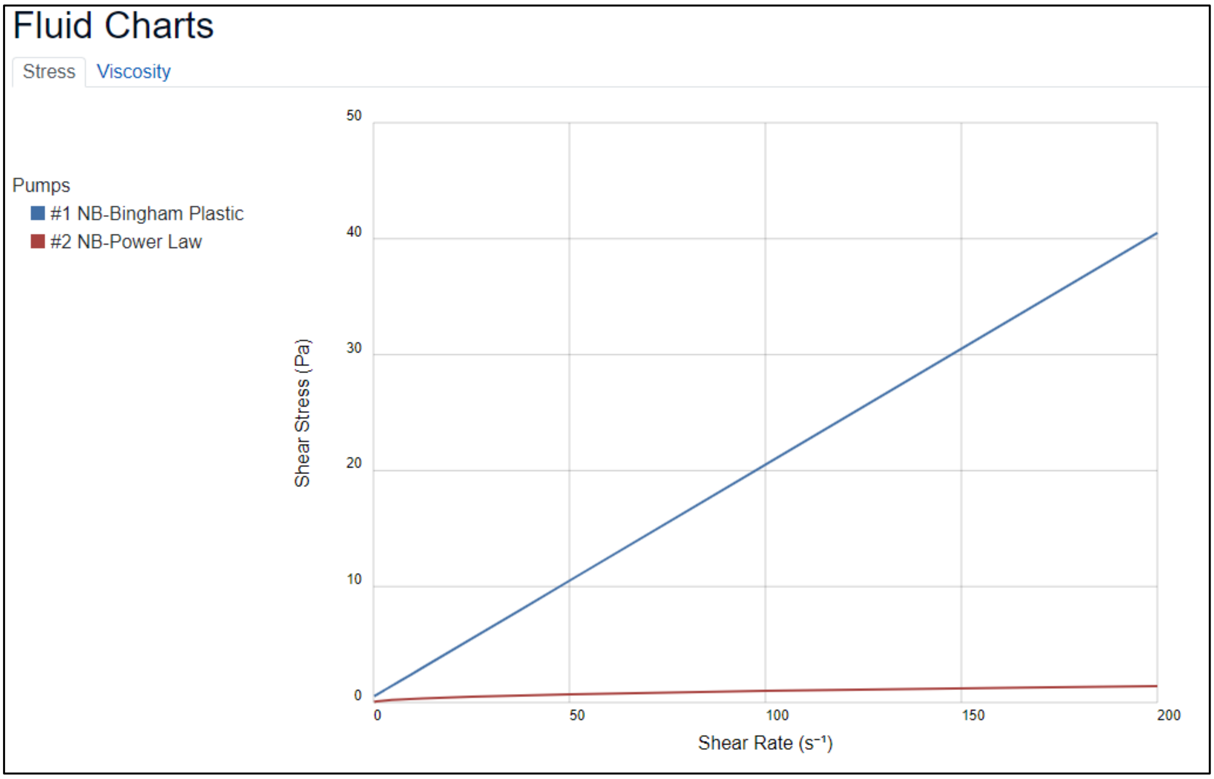


Figure 6 – Shear Stress vs Shear Rate Curve

and viscosity against shear rate (where viscosity is given by the ratio of shear stress to shear rate, or the gradient of the above curve):

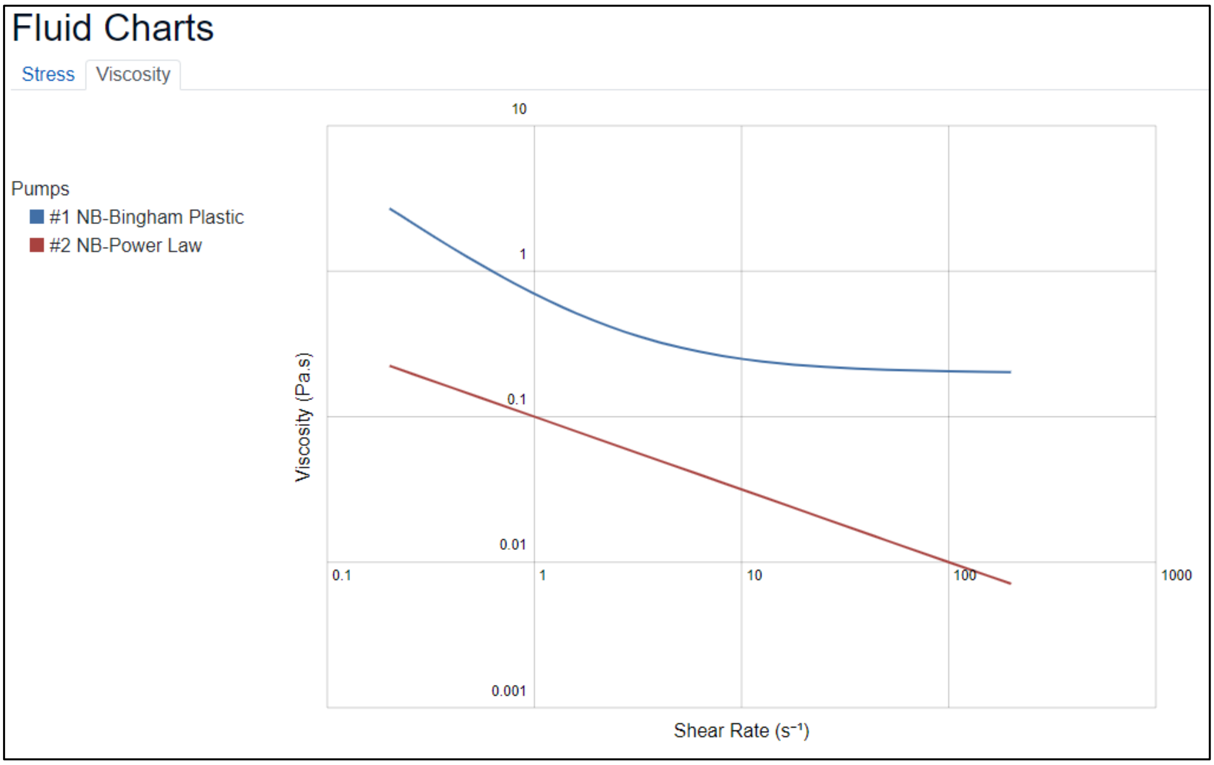


Figure 7 – Viscosity vs Shear Rate Curve

3.2.2 Pump

When assigning a pump to the Job the 'Pump Item' page features the following options to be selected:

Input Parameter	Options
Type *	Positive Displacement - Gear
	Positive Displacement - Lobe
	Positive Displacement - Peristaltic
	Positive Displacement - Progressive Cavity
	Positive Displacement - Reciprocating
	Positive Displacement - Screw
	Positive Displacement - Vane
	Rotodynamic - Axial
	Rotodynamic - Centrifugal
	Rotodynamic - Mixed Flow
	Unspecified
Pump *	Select pump 'Name' already created
Speed [rpm] * [1]	Number (1 to 1000)
Rated Speed [rpm] *	Automatically selected
Configuration * [2]	None
	In Parallel
	In Series
Number *	Whole number (of pumps in parallel or series)

[1] If a pump speed is assigned that is different to the pump rated speed then the pump curve assigned in the Stock Pump item will be scaled according to the Affinity Laws described in Section 5.6.1. These scalings only apply to Rotodynamic pumps, so for Positive Displacement pumps the Speed input should always match the Rated Speed, even though different speeds are allowed to be entered.

[2] When a pump configuration 'In Parallel' or 'In Series' is selected the pump curve assigned in the Stock Pump item will be scaled according to the rules described in Section 5.6.2.

3.2.3 Component

When assigning a component to the Job the ‘Component Item’ page features the following options to be selected:

Input Parameter	Options
Type *	Bend
	Expander
	Orifice
	Pipe
	Pump
	Reducer
	Tank
	Tee
	User Defined
	Valve
Component * [1]	Select component ‘Name’ already created
Multiplier * [2]	Whole number
Notes [3]	Text, to be created

[1] The Stock Component should be named carefully to be able to find among the list of created components; include fitting type, dimensions, *etc.*

[2] The multiplier is used to combine multiple parts into a single pressure loss term. The form only allows components of exactly the same fittings type and dimensions to be combined. In order for the Pressure Profile obtained to be correct (see Section 2.3.3) the components should also be at the same elevation.

[3] For example, enter part number or describe parts are being combined.

4 Results

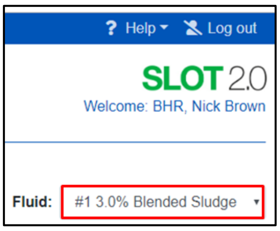
4.1 Analyse

Once a valid job has been created with fluids, pumps and components, click the 'Analyse' button to get the Analysis page, a new page appears:

The following warnings are delivered if a valid job has not been created:

- Inconsistency of fitting diameters in order of components
- No Fluid
- No Components

Different fluids can be selected using the 'Fluid:' drop-down box:



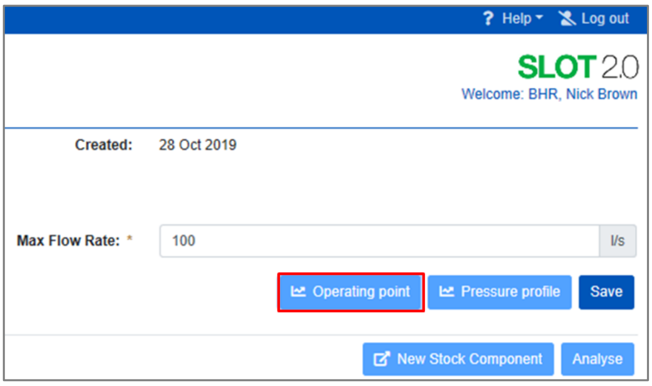
The following variables are output on the Analysis page:

<table>
<tr><th colspan="2">Variable</th><th>Unit</th><th>Description</th></tr>
<tr><td colspan="2">Component Name</td><td>-</td><td>Text</td></tr>
<tr><td colspan="2">Type</td><td>-</td><td>Text: Component Type</td></tr>
<tr><td colspan="2">V</td><td>m/s</td><td>Mean velocity through component inlet</td></tr>
<tr><td colspan="2">Re effective</td><td>-</td><td>Reynolds number at component inlet</td></tr>
<tr><td colspan="2">Re down</td><td>-</td><td>Reynolds number at component outlet</td></tr>
<tr><td colspan="2">Regime</td><td>-</td><td>Laminar or Turbulent</td></tr>
<tr><td colspan="2">ff</td><td>-</td><td>Fanning friction factor for pipes</td></tr>
<tr><td colspan="2" rowspan="2">K</td><td rowspan="2">-</td><td>ff $\times 4L/D$, for pipes</td></tr>
<tr><td>Fitting Loss Coefficient (k in Equ. (40)) for fittings</td></tr>
<tr><td rowspan="5">ΔP,
P Upstream,
P Downstream</td><td>Friction</td><td>m.fluid</td><td>Pressure due to frictional losses</td></tr>
<tr><td>Internal</td><td>m.fluid</td><td>Internal pressure</td></tr>
<tr><td>Potential</td><td>m.fluid</td><td>Pressure due to elevation changes</td></tr>
<tr><td>Dynamic</td><td>m.fluid</td><td>Pressure due to changes in flow speed/diameter</td></tr>
<tr><td>Total</td><td>m.fluid</td><td>Overall pressure due to above components</td></tr>
</table>

An example of the Analysis screen is shown in Section 2.3.1.

4.2 Operating Point

The system pressure loss curves are plotted along with the pump curves using the Operating point button, which again opens a new window:



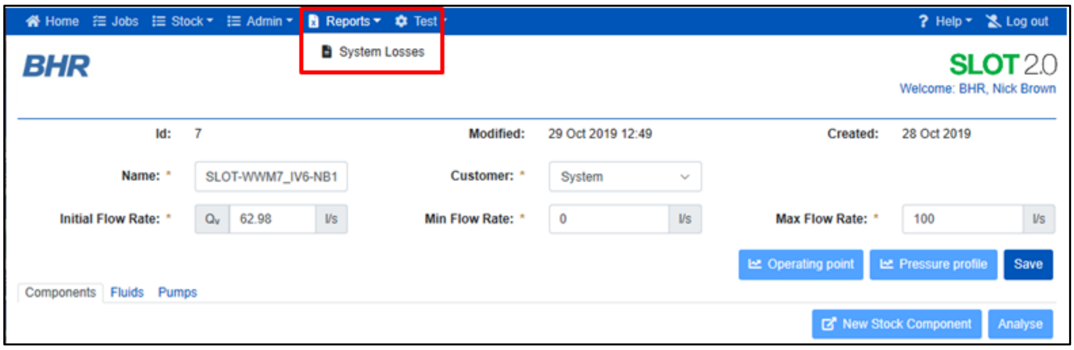
The relevant fluids for the system curves and pumps for the pump curves can be selected using tick boxes on the top left hand side of the screen (see Figure 3). Hovering the cursor over the intersection point shows the precise operating point coordinates.

4.3 Pressure Profile

The Pressure Profile for the system of components can be examined using the 'Pressure Profile' button (see Figure 5). Note, for the Piezometric and Potential pressures to match at the end of the network profile the correct flow rate must be selected and correct 'Head Added' selected in the Pump Component within the Job, corresponding to the system Operating Point under consideration. This is detailed more in Section 2.3.3. The data underlying the Pressure Profile graph can be exported to Excel format using the 'Download Report' button.

4.4 Reports – System Losses

Once the 'Analyse' button has been clicked on the Job the 'System Losses' report becomes available in the Reports tab:



This exports a summary of the results in an Excel format, appearing at the bottom left corner of the screen. After opening the ‘System Losses’ Excel sheet the ‘Enable Editing’ button needs to be clicked for the data in the ‘Report’ tab to be visible.

5 Theory

This section describes the methodology followed by SLOT 2.0 for the calculation of pressure losses for Newtonian and non-Newtonian fluids in pipeline systems.

5.1 Overall System Losses

For the calculation of the pressure losses in a pipeline system a simple one-dimensional treatment is applied. The fluid is assumed to be homogeneous and incompressible. Between two points in a system the pressure loss is equal to the difference in the total pressures

$$\Delta P = P_{T,1} - P_{T,2} \tag{1}$$

where the total pressure is the sum of the internal, dynamic and potential pressures

$$P_T = p + \tfrac{1}{2}\rho\overline{V}^2 + \rho g z \tag{2}$$

or

$$\Delta P = \left(p_1 + \tfrac{1}{2}\rho\overline{V}_1{}^2 + \rho g z_1\right) - \left(p_2 + \tfrac{1}{2}\rho\overline{V}_2{}^2 + \rho g z_2\right) \tag{3}$$

where $\bar{V}$ is the average velocity of the fluid over a pipe cross-section, p is the internal pressure, z is the elevation.

From knowledge of the volumetric flow rate and of the geometric arrangement of the system, pressure losses are calculated for each section of pipe and for each component. Elevation is specified in SLOT 2.0 relative to the previous component rather than to a reference datum, with positive z being in the vertically upward direction. The overall pressure loss for incompressible flow is given by the sum of the individual pressure losses.

5.2 Rheology

5.2.1 Rheological Models / Flow Curves

The loss through a component depends on the rheological properties of the fluid and SLOT 2.0 can use various rheological models to describe the behaviour of the fluid under consideration. These models are expressed as a relationship between the shear rate, $\dot{\gamma}$, and shear stress, τ. In all cases it is assumed that the fluid's rheology is isotropic, having no dependence on the direction of measurement, and does not depend on the history of deformation, *i.e.* the rheological properties are time-independent.

The rheological models considered in SLOT 2.0 are as follows:

1. **Newtonian**

$$\tau = \mu\dot{\gamma} \tag{4}$$

This is the simplest model and assumes a linear relationship between the shear rate and shear stress in which the viscosity is constant. The parameter of proportionality is the viscosity, μ, of the fluid. Pure water is described by the Newtonian model.

2. **Power Law**

$$\tau = K\dot{\gamma}^{n} \tag{5}$$

Many sludges are described by this two parameter model. The parameters are the Consistency Index, K, and the Power Law Index, n. The Power Law model collapses to the Newtonian one for $n = 1$. Most sewage sludges are shear thinning, *i.e.* as the shear rate increases, the effective viscosity reduces, which means that $n < 1$.

3. **Bingham Plastic**

$$\tau = \tau_y + \mu_p\dot{\gamma}\,, \qquad \tau > \tau_y \tag{6}$$

$$\dot{\gamma} = 0\,, \qquad \text{otherwise}$$

Fluids which may be described by the Bingham Plastic model need a minimum value of shear stress in order to be sheared. However, the yield stress in the model, τ_y, is a curve fitting parameter to experimental data. What defines the minimum shear stress, which must be exceeded for fluid motion to occur, is the static yield stress, τ_0, which needs to be measured separately and cannot be predicted from the yield stress parameter in the Bingham plastic model. The static yield stress is used in SLOT 2.0 to predict the pump start-up pressure (see Section 5.5).

For the Bingham Plastic model there is a linear relationship between the shear stress and shear rate, with $\tau = \tau_y$ for zero shear rate and a gradient equal to the plastic viscosity, μ_p. This two parameter model collapses to Newtonian for zero yield stress, τ_y.

4. **Herschel-Bulkley**

$$\tau = \tau_y + K\dot{\gamma}^n, \qquad \tau > \tau_y \tag{7}$$

$$\dot{\gamma} = 0, \qquad \text{otherwise}$$

The Herschel-Bulkley model constitutes the most general rheological description in SLOT 2.0. The model collapses to the Bingham Plastic model if $\mathrm{n} = 1$, and to the Power Law model if $\tau_y = 0$. A fluid described by the Herschel-Bulkley model will also have an associated static yield stress, which must be exceeded for fluid motion. Again this static yield stress is different from the yield stress,τ_y, in the Herschel-Bulkley model and must be measured separately.

The general shape of the different flow curve models is illustrated in Figure 8.

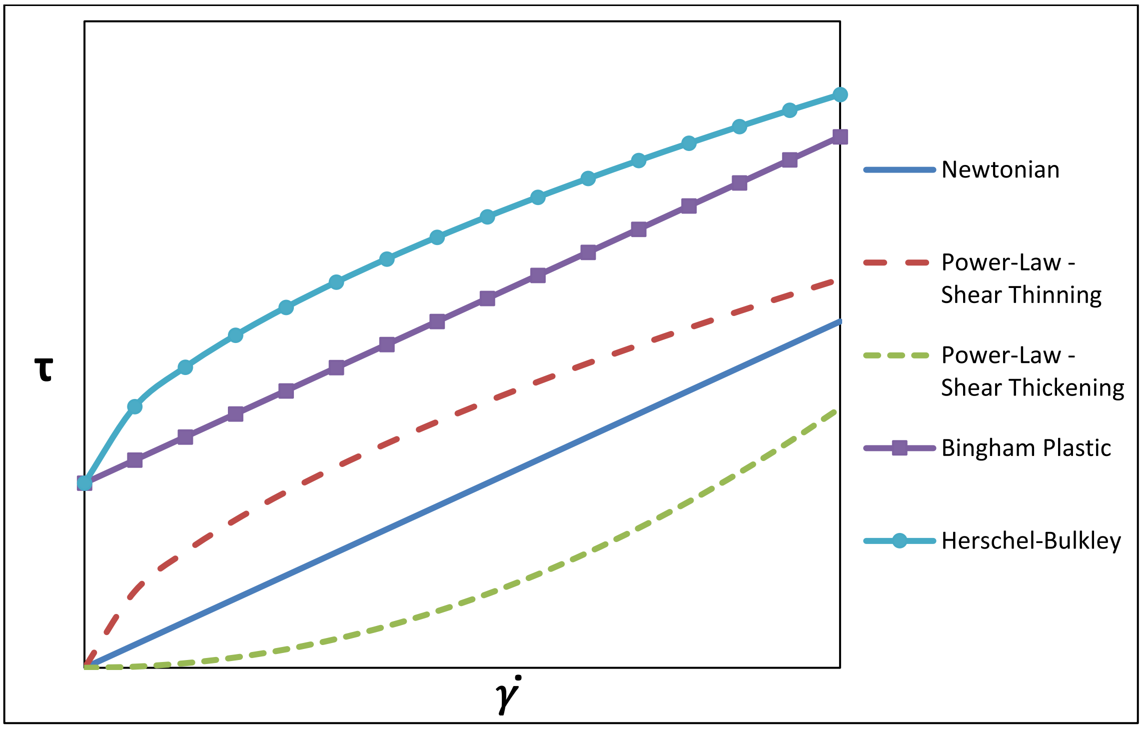


Figure 8 – Flow Curves

5.2.2 Sludge Rheology Database

The Sludge Rheology Database (SRDB) is a database holding rheological information from around 500 sewage sludge samples and was initially established in MS Access for the WWM research programme run by BHR. It was then expanded to include a Web-based correlation calculator tool which predicted the fitted flow curve model parameters for a variety of sludge types, origins, temperatures and dry solids content. The SRDB correlation calculator also gives prediction limits to allow estimates of the probability of the flow curve being within the given limits due to the scatter in the underlying data.

The SRDB correlation calculator has been incorporated within SLOT 2.0 as the Herschel-Bulkley Coefficient Picker tool, which is accessed when a Herschel-Bulkley fluid is selected from the Stock Fluid dialogue. The following sections detail the methodology behind the SRDB correlation calculator, which is summarised in the WWM reports CR 8099 [1] and CR 8249 [2].

Raw Data

- Rheological measurements were undertaken for the sludge samples and torque and speed (rpm) data were obtained.
- The torque values and speed values were converted to shear stress and shear rate based on the rheometer geometry.
- Raw data (shear stress, shear rate, DS%, temperature) of a particular sludge type were tabulated together.

Model fitting for Raw Data

- The shear stress and shear rate data was then curve fitted using two Herschel-Bulkley methods (unweighted and weighted).
- The unweighted method involved three degrees of freedom and an iterative process to calculate and minimise the error between the data and the Herschel-Bulkley model curve.
- The weighted method involved a single degree of freedom and a regression analysis along with iteration to get the value of regression coefficient, R^2 closest to 1.
- The values of τ_y, K and n were determined using regression analysis.

Variation of shear stress with DS%

- The sludge data were first grouped into different categories (e.g. digested, primary etc.)
- Values of the experimental shear stress at discrete specified shear rates were tabulated (shear rate range from $3s^{-1}$ to $200s^{-1}$). A temperature of 10°C was used as a base for data comparison. If the experimental data were obtained at a different temperature a correction factor was used (see Temperature Correction Factor below).
- For each discrete value of shear rate, a graph of the shear stress vs DS% was plotted, and a power law trend-line was fitted by performing a linear regression.
- This formed the basis of predicting shear stress based on DS% and a temperature of 10°C, for a chosen sludge category and shear rate.

Temperature Correction Factor (TCF)

- The viscosity-temperature relationship of a suspension may be assumed to be given by that of the suspending liquid alone at a given shear rate (Viswanath and Natarajan, 1989 [4])
- The apparent viscosities of the sludge can therefore be scaled by a Temperature Correction Factor (TCF) given by the ratio of water viscosities at the different temperatures.
- It follows that the same TCF can be used to predict the shear stress for a particular solid content and temperature, scaled for a different temperature.

Model fitting for grouped data

- By choosing a specific sludge category, DS% content and temperature, all the trend-lines for each shear rate (over the different samples) were used to give the relevant shear stress values.
- These were then fitted by both the weighted and unweighted Herschel-Bulkley model.
- Hence, the mean Herschel-Bulkley parameters τ_y, k and n for a particular sludge category, DS% and temperature were calculated.

Prediction Limits

As more samples were introduced into the SRDB, and thus the power of analysis was increased, it became clear that a calculation of the error margins for the calculated flow properties was required, and the initial categories formed were revisited to confirm their validity and updated as necessary.

The error margins were obtained by determining upper and lower 95% Prediction Limits on the shear stress and *DS%* correlations for each sludge category at 10°C, performing a linear regression on the transformed power-law equation:

$$\ln\tau = \ln a_j + b_j \ln(DS\%) \qquad \text{for } j = 1,2,\ldots,16 \qquad (8)$$

Prediction Limits enable one to predict with a certain probability (*eg.* 0.95 probability for 95% limit) if the Random Variable associated with a data set ($\ln\tau$ in the above case) will fall within that limit. This is in contrast to **Confidence Limits** which predict with a certain probability if a parameter of the data, commonly the mean, will fall within that limit. Confidence intervals for the mean are much narrower than prediction intervals and so can give an exaggerated sense of accuracy to forecasts using this method. Hence, prediction limits were employed in the SRDB correlation calculator.

Lines corresponding to the upper and lower 95% limits ($\ln\tau$ against $\ln(DS\%)$) were constructed and converted back to the power law fit. The same procedure was followed for all the sets of data corresponding to every shear rate separately.

The upper and lower predicted stresses based on *DS%* at the given temperature of 10° were then modified using the TCF described above to apply to different temperatures.

Finally the upper and lower values of the rheological parameters (τ_{yHB}, k and n) were calculated based on a model fit using the Herschel-Bulkley correlation for shear stress against shear rate, as described above in ‘Model fitting for grouped data’.

Sludge Categorisation

Different samples of sludge were compared using two methods [3], namely the signed-rank test (non-parametric) and unpaired 2-sample student’s t-test (parametric), to determine whether they belonged to the same population.

To define all the distinctive categories, the samples were grouped together with their respective undertaken processes. There were six top level categories: Primary, Secondary, Hydrolysed, Potable, Digested and Blended. Then, depending on the top level category, the secondary and tertiary descriptors included thickened/unthickened, thickening method, co-settled, polymer dosed, coagulant dosed, etc.

As expected, the samples from different main processes were found not to have any similar rheology. The list below shows the final separate sludge categories as found using the statistical tests performed:

Main No.	Main Process	Secondary / Tertiary Process
1	Primary	Unthickened (including co-settled)
		Unthickened, Fe dosed (including co-settled)
		Thickened (Belt) or Blend of thickened/unthickened
		Thickened (Gravity or Drum)
2	Secondary	SAS, thickened (Gravity or Drum)
		SAS, thickened (Belt), Polymer dosed
		SAS, thickened (Belt), Polymer and Coagulant dosed
3	Hydrolysed	Enzymically Hydrolysed (including enhanced)
		Pasteurised - Alpha Biotherm
		Thermally Hydrolysed – CAMBI
4	Potable	Thickened
5	Digested	Unthickened (including EH feed)
		Thickened
		Thermally Hydrolysed – CAMBI
6	Blended	Thickened (either or both streams)
		Unthickened

Table 1 – Sludge Categories in SRDB Correlation Calculator

5.3 Flow Through Straight Pipes

A pressure loss occurs in straight pipes due to the friction exerted by the wall on the fluid, which results in internal fluid friction. The ‘no-slip’ assumption states that the flow velocity is reduced to zero at the (stationary) wall. As a consequence a viscous fluid will experience a shear stress, and the resulting frictional pressure loss in a circular conduit, ΔP, may be related to the wall shear stress, τ_w, the pipe length, L, and internal diameter, D, by

$$\Delta P = \frac{4L}{D}\tau_w \tag{9}$$

For convenience a dimensionless quantity, f, known as the **Fanning friction factor**, may be defined by the following relation

$$\tau_w = \frac{1}{2}\rho\overline{V}^2 f \tag{10}$$

When referring to friction factors it should be noted that there is also a Darcy friction factor which is commonly used in frictional pressure loss calculations. The Darcy friction factor is four times the Fanning friction factor.

5.3.1 Pipe Reynolds Number

The Reynolds number is a dimensionless number that gives a measure of the ratio of inertial forces to viscous shear forces. The description of the Reynolds number for the pipe flow depends on the rheological behaviour of the fluid.

For a **Newtonian** fluid the pipe Reynolds number is expressed by

$$\mathrm{Re}_{\mathrm{N}} = \frac{\rho\overline{V}D}{\mu} \tag{11}$$

For a **Power Law** fluid, Metzner & Reed (1955, [1]) proposed the use of a Reynolds number which has a unique solution for the Fanning friction factor in a pipe for laminar flow, similar to the Newtonian, *i.e.* $f = 16/\mathrm{Re}_{\mathrm{PL}}$. This is expressed as

$$\mathrm{Re}_{\mathrm{PL}} = \frac{\rho\overline{V}^{2-n}D^n}{8^{n-1}K}\left(\frac{4n}{1+3n}\right)^n \tag{12}$$

For the case of a **Bingham Plastic** (which involves a plastic viscosity, μ_p, see Equation (6)), the pipe Reynolds number is described by

$$\mathrm{Re}_{\mathrm{B}} = \frac{\rho \overline{V} D}{\mu_{\mathrm{p}}} \tag{13}$$

For a **Herschel-Bulkley** fluid, Slatter (1999, [6]) proposed a method in which the Reynolds number is determined by the ratio of the inertial forces to viscous forces only in the sheared portion of the flow (the annulus), whereas the un-sheared plug is treated as a solid body in the middle of the pipe:

$$\mathrm{Re}_{\mathrm{HB}} = \frac{8\rho V_{\mathrm{ann}}^2}{\tau_y + K\left(\frac{8V_{\mathrm{ann}}}{D_{\mathrm{shear}}}\right)^n} \tag{14}$$

Here the characteristic length of the sheared annulus is

$$D_{\mathrm{shear}} = D - D_{\mathrm{plug}} \tag{15}$$

The mean velocity in the annulus is

$$V_{ann} = \frac{Q_{ann}}{A_{ann}} = \frac{Q - Q_{plug}}{A - A_{plug}} \tag{16}$$

The ratio of the diameter of the plug to the diameter of the pipe is

$$\frac{D_{\mathrm{plug}}}{D} = \frac{\tau_y}{\tau_w} = x \tag{17}$$

The required plug flow quantities to determine $\mathrm{Re}_{\mathrm{HB}}$ are

$$A_{\mathrm{plug}} = \frac{\pi D_{\mathrm{plug}}^2}{4}, \qquad Q_{\mathrm{plug}} = V_{\mathrm{plug}} A_{\mathrm{plug}} \tag{18}$$

with the velocity of the plug given by

$$V_{\mathrm{plug}} = \frac{D}{2K^{1/n}\tau_w} \frac{n}{n+1} \left(\tau_w - \tau_y\right)^{\frac{n+1}{n}} \tag{19}$$

The mean velocity over the whole pipe cross-section may be determined by the following expression,

$$\overline{V} = \frac{D}{8}\left(\frac{4n}{3n+1}\right)\left(\frac{\tau_w}{K}\right)^{1/n}(1-x)^{1/n}\left[1-\left(\frac{x}{2n+1}\right)\left(1+\frac{2nx}{n+1}(1+nx)\right)\right] \tag{20}$$

This equation requires an iterative calculation of x and τ_w given the known mean velocity from the overall flow rate, and ultimately allows the Reynolds number to be determined from the above quantities.

5.3.2 Laminar Frictional Losses in Pipes

For a **Newtonian** fluid the Fanning friction factor is described by

$$f = \frac{16}{\mathrm{Re_N}} \tag{21}$$

For a **Power Law** fluid the Reynolds number was designed to be such that frictional loss is expressed in a similar way as for the Newtonian fluid

$$f = \frac{16}{\mathrm{Re_{PL}}} \tag{22}$$

Due to the existence of a yield stress parameter for a **Bingham Plastic** fluid the calculation of the friction factor is not explicit and needs iteration. It is described as

$$f = \frac{16}{\mathrm{Re_B}}\left(1 + \frac{\mathrm{He}}{6\,\mathrm{Re_B}} + \frac{\mathrm{He}^4}{3 f^3\,\mathrm{Re_B^7}}\right) \tag{23}$$

where He is the Hedström number, with μ_p and τ_y defined in Equation (6):

$$\mathrm{He} = \frac{\rho D^2 \tau_y}{\mu_\mathrm{p}} \tag{24}$$

For a **Herschel-Bulkley** fluid the Fanning friction factor may be described as a function of the Power Law Reynolds number (setting τ_y to zero in the Herschel-Bulkley model), using the following implicit equation (Garcia & Steffe, 1987 [7]):

$$f = \frac{16}{\psi\,\mathrm{Re_{PL}}} \tag{25}$$

where

$$\psi = (1+3n)^n (1+x)^{1+n}\left[\frac{(1-x)^2}{1+3n} + \frac{2x(1-x)}{1+2n} + \frac{x^2}{1+n}\right] \tag{26}$$

and x is the ratio of the yield stress to the wall shear stress as defined in Equation (17).

5.3.3 Turbulent Frictional Losses in Pipes

In turbulent flow the frictional losses depend on the rheological properties, the Reynolds number and the roughness of the internal pipe wall. There are no fully analytical ways of deriving equations for calculating the losses in the turbulent regime, although many methods have been obtained empirically for predicting the frictional losses. The methods used in SLOT 2.0 are presented as follows:

For a **Newtonian** fluid in the turbulent regime the Fanning friction factor is calculated using the Colebrook-White equation. The equation is implicit in the friction factor and therefore iteration is required

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon}{3.7D} + \frac{2.51}{\mathrm{Re}_{\mathrm{N}}\sqrt{f}}\right) \tag{27}$$

where ε is the absolute inner wall roughness. Roughness values are given for some commercial pipes in Table 2, but note that these values are for new pipes and roughness may increase with age as a result of corrosion, scale build-up and precipitation [8].

Material	Roughness, ε [mm]
Concrete	0.9 – 9
Rubber, smoothed	0.01
Copper or brass	0.0015
Cast iron	0.26
Galvanised iron	0.15
Wrought iron	0.046
Stainless steel	0.002
Commercial steel	0.045

Table 2 – Absolute Roughness Values for New Commercial Pipes [8]

For all non-Newtonian models in the turbulent regime the Fanning friction factor is calculated using the method developed by Wilson and Thomas ([9], [10]). This method is based on the assumption that the viscous sublayer thickness increases when the fluid is non-Newtonian compared to a Newtonian fluid. The viscous sublayer thickness is defined as the ratio of the area under the non-Newtonian rheogram, to that for a Newtonian fluid with the same shear rate and wall shear stress. The mean velocity is always of the form

$$\bar{V} = V_{\mathrm{N}} + u^{*}\beta \tag{28}$$

where $u^* = \sqrt{\tau_w/\rho}$ is known as the shear velocity, and V_{N} is the equivalent velocity for a Newtonian fluid. This Newtonian velocity can be calculated using Equation (10), using the same wall shear stress and density, and the Newtonian friction factor from Equation (27) for a Newtonian Reynolds number ($\mathrm{Re} = \rho D V_N/\mu_{\mathrm{eff}}$) and the appropriate roughness value. The calculation of the effective viscosity, μ_{eff}, and the function β, depend on the rheological behaviour of the fluid modelled.

For a **Power Law** fluid the parameter β is given by

$$\beta = 2.5\ln\left(\frac{n+1}{2}\right) + 11.6\left(\frac{1-n}{n+1}\right) \tag{29}$$

and the effective viscosity is estimated by

$$\mu_{\mathrm{eff}} = K\left(\frac{3n+1}{4n}\right)^{n}\left(\frac{8V}{D}\right)^{n-1} \tag{30}$$

For a **Bingham Plastic** fluid the parameter β is equal to

$$\beta = 2.5\ln\left(\frac{1-x}{1+x}\right) + x(14.1 + 1.25x) \tag{31}$$

and the effective viscosity is calculated by

$$\mu_{\mathrm{eff}} = \frac{\mu_p}{1-x} \tag{32}$$

For a **Herschel-Bulkley** fluid the parameter β is equal to

$$\beta = 2.5\ln\left[\frac{(1-x)(1+n)}{2(1+xn)}\right] + 1.25x^2 + \left(\frac{25.7n+2.5}{n+1}\right)x + 11.68\left(\frac{1-n}{1+n}\right) \tag{33}$$

and the effective viscosity is calculated by

$$\mu_{\mathrm{eff}} = \left[\frac{K}{(1-x)\tau_w}\right]^{\frac{1}{n}}\tau_w \tag{34}$$

The equations for each non-Newtonian flow model are solved iteratively together with the formulae for mean velocity, shear velocity, Newtonian friction factor and Reynolds number, described above, to calculate the wall shear stress. Equation (10) is then used to solve for the Fanning friction factor.

5.3.4 Transition from Laminar to Turbulent Flow

The transition point between the laminar and turbulent flow regimes is defined by the critical Reynolds number, which defines the different regions where the equations for laminar or turbulent friction factors are used. The critical Reynolds numbers used in SLOT 2.0 are given as follows:

For a **Newtonian** fluid

$$\mathrm{Re}_{\mathrm{N},c} = 2100 \tag{35}$$

For a **Power Law** fluid (Ryan & Johnson, 1959 [11])

$$\mathrm{Re}_{\mathrm{PL},c} = \frac{6464n(n+2)^{\frac{n+2}{n+1}}}{(1+3n)^2} \tag{36}$$

For a **Bingham Plastic** fluid (Wasp et al, 1977 [12])

$$\mathrm{Re}_{\mathrm{B},c} = 1500\left(1+\sqrt{1+\frac{He}{4500}}\right) \tag{37}$$

For a **Herschel-Bulkley** fluid (Slatter, 1999 [6])

$$\mathrm{Re}_{\mathrm{HB},c} = 2100 \tag{38}$$

5.4 Frictional Losses in Fittings

The pressure loss in fittings is defined as the difference in overall pressure between the ends of two long straight pipes when there is a fitting installed and when there is no fitting. Figure 9 shows the effect of this pressure loss on the pipe hydraulic grade lines.

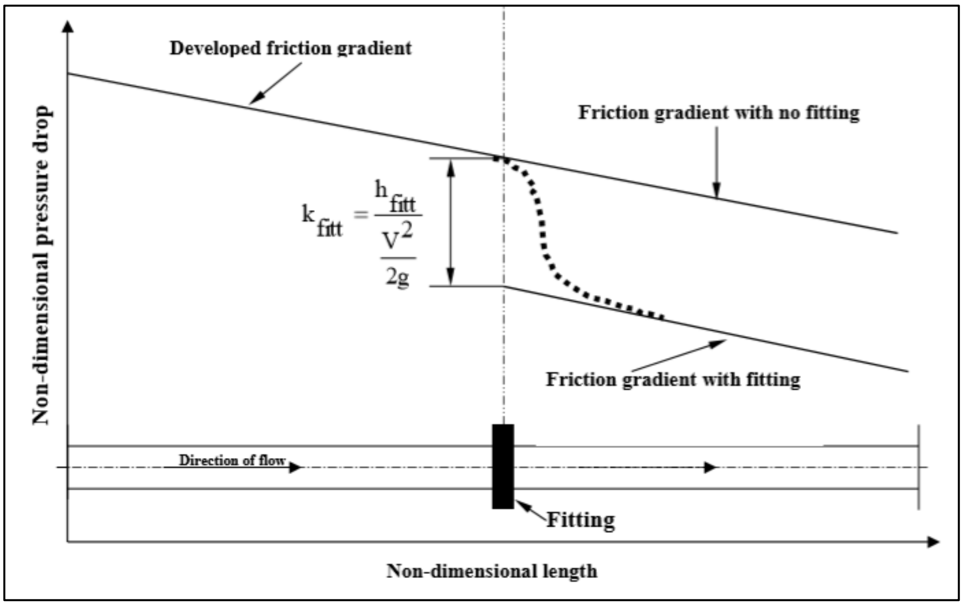


Figure 9 – Definition of Fitting Loss Coefficient

The head losses in turbulent flow are found to be approximately proportional to the mean velocity squared. As a consequence the pressure loss is traditionally modelled as a function of the mean dynamic pressure,

$$\Delta P = k\frac{1}{2}\rho\overline{V}^2 \qquad (39)$$

where k is the fitting loss coefficient. In the laminar regime, the loss coefficients for fittings are dependent on Reynolds number. The losses also depend on the internal diameter of the fitting (scale effect). There are many different methods for estimating the loss coefficients in both laminar and turbulent regimes.

SLOT 2.0 uses the two-*K* correlation derived by Hooper (1981, [13]), which enables prediction of a fitting loss coefficient applicable to both laminar and turbulent flow, including the scale effect, and without the need for defining a point of transition. The equation is a function of the Reynolds number and fitting internal diameter,

$$k = \frac{k_1}{\mathrm{Re}} + k_\infty\left(1 + \frac{0.0254}{D}\right) \qquad (40)$$

The two coefficients depend only on the geometry of the fitting. The values of k_1 and k_∞ are summarised in Table 3.

Pipe Fittings	k_1	k_∞
Elbow / bend 90°; standard (R/D=1), threaded	800	0.40
Elbow / bend 90°; standard (R/D=1), flanged or welded	800	0.25
Elbow / bend 90°; long radius (R/D=1.5), all types	800	0.20
Elbow / bend 45°; standard (R/D=1), all types	500	0.20
Elbow / bend 45°; long radius (R/D=1.5), all types	500	0.15
Elbow / bend 180°; standard (R/D=1), all types	1000	0.60
Elbow / bend 180°; long radius (R/D=1.5), all types	1000	0.35
Tee (elbow / branch); standard, threaded	500	0.70
Tee (elbow / branch); long radius, threaded	800	0.40
Tee (elbow / branch); standard, flanged or welded	800	0.80
Tee (run through); threaded	200	0.10
Tee (run through); flanged or welded	150	0.50
Gate valve (open)	300	0.10
Globe valve, standard (open)	1500	4.00
Globe valve, angle or Y-type (open)	1000	2.00
Diaphragm valve (open)	1000	2.00
Butterfly valve	800	0.25
Check valve (lift type)	2000	10.0
Check valve (swing)	1500	1.50
Check valve (tilting)	1000	0.50

Table 3 – Hooper 2K Coefficient Values for Various Fittings

For a Converging Tee, which is automatically specified if the additional flow is positive, the loss coefficient Reynolds number is based on the inlet flow, while for a Diverging Tee, which is specified if the additional flow is negative, it is based on the outlet flow (see Figure 10).

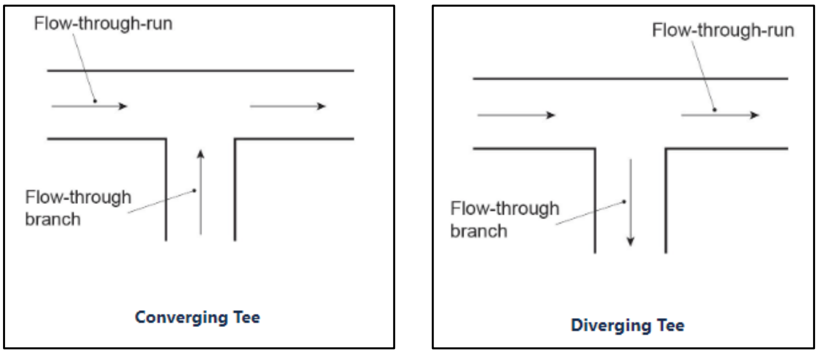


Figure 10 – Converging and Diverging Tees

SLOT 2.0 uses loss coefficients for entrances or exits from tanks to pipes using the following correlation (Hooper (1981, [13]):

$$k = \frac{k_1}{Re} + k_\infty \tag{41}$$

Values of k_1 and k_∞ are given in Table 4 (Hooper, 1981 [13]) and Table 5 (Darby, 2001 [14]), for square and rounded pipe entrances respectively.

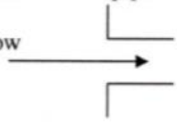
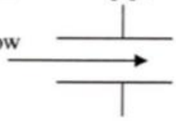
	k_1	k_∞
pipe entrance: flush, square *tank* *pipe* flow 	160	0.5
pipe entrance: inward-projecting (Borda) *tank* *pipe* flow 	160	1.0
pipe exit (all geometries)	0	1.0

Table 4 – Loss coefficient values for square pipe entrance from tank or pipe exit to tank

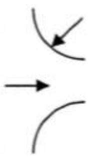
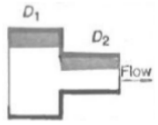
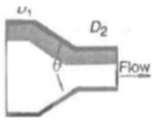
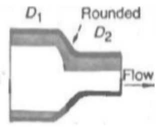
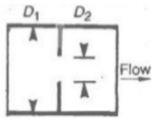
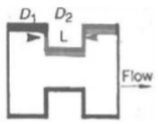
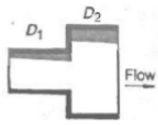
	r/D	k_1	k_∞
 r D	0.0 (sharp)	160 for all r/D	0.5
	0.02		0.28
	0.04		0.24
	0.06		0.15
	0.10		0.09
	0.15 (and up)		0.04

Table 5 – Loss coefficient values for rounded exit from tank to pipe

SLOT 2.0 uses loss coefficients for reducers, expanders and orifices as defined in Table 6 (Hooper, 1988 [15]), where kfitt is equivalent to the loss coefficient, k, in Equation (38).

Case	Fitting	Inlet Re	k_{fitt} based on inlet velocity	
A	Square reduction 	≤ 2500	$k_{fitt} = \left[1.2 + \frac{160}{Re_N}\right]\left[\left(\frac{D_1}{D_2}\right)^4 - 1\right]$	
		> 2500	$k_{fitt} = \left[0.6 + 1.92f\right]\left(\frac{D_1}{D_2}\right)^2 \left[\left(\frac{D_1}{D_2}\right)^2 - 1\right]$	
B	Tapered reduction 	All	Multiply k_{fitt} from Case A by $\sqrt{\sin\left(\frac{\theta}{2}\right)}$	$45^\circ < \theta < 180^\circ$
			Multiply k_{fitt} from Case A by $1.6\sin\left(\frac{\theta}{2}\right)$	$0^\circ < \theta < 45^\circ$
C	Pipe reducer 	All	$k_{fitt} = \left[0.1 + \frac{50}{Re_N}\right]\left[\left(\frac{D_1}{D_2}\right)^4 - 1\right]$	

Case	Fitting	Inlet Re	k_{fitt} based on inlet velocity	
D	Thin sharp orifice 	≤ 2500	$k_{fitt} = \left[2.72 + \left(\frac{D_2}{D_1}\right)^2\left(\frac{120}{Re_N} - 1\right)\right]\left[1 - \left(\frac{D_2}{D_1}\right)^2\right]\left[\left(\frac{D_1}{D_2}\right)^4 - 1\right]$	
		> 2500	$k_{fitt} = \left[2.72 - \left(\frac{D_2}{D_1}\right)^2\left(\frac{4000}{Re_N}\right)\right]\left[1 - \left(\frac{D_2}{D_1}\right)^2\right]\left[\left(\frac{D_1}{D_2}\right)^4 - 1\right]$	
E	Thick orifice 	All	Use Case A and Case F	$L/D_2 > 5$
			Multiply k_{fitt} from Case D by $0.584 + \left[\frac{0.0936}{(L/D)^{1.5} + 0.225}\right]$	$L/D_2 \leq 5$
F	Square expansion 	≤ 4000	$k_{fitt} = 2\left[1 - \left(\frac{D_1}{D_2}\right)^4\right]$	
		> 4000	$k_{fitt} = \left[1 + 3.2f\right]\left[1 - \left(\frac{D_1}{D_2}\right)^2\right]^2$	

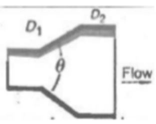
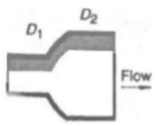
Case	Fitting	Inlet Re	k_{fitt} based on inlet velocity	
G	Tapered expansion 	All	Use k_{fitt} from Case F	$\theta > 45^\circ$
			Multiply k_{fitt} from Case F by $2.6\sin\left(\frac{\theta}{2}\right)$	$\theta < 45^\circ$
H	Pipe expander 	All	Use k_{fitt} for Case F	

Table 6 – Loss coefficient values for reducers, expanders and orifices

The frictional loss coefficients defined in this section were originally determined for Newtonian fluids. However, Edwards *et. al.* (1985, [16]) found that the Hooper two-*K* fitting losses were similar for both the Newtonian and non-Newtonian fluids if the appropriate Reynolds number (see Section 4.3.1) was defined according to the correct fluid flow property. This effectively means that the fittings loss correlations can be utilised for non-Newtonian fluids as long as the appropriate Reynolds number is used in Equation (40). Therefore, this is the method implemented in SLOT 2.0 for all fittings, applicable to all scales, laminar/turbulent regimes, and for both Newtonian and non-Newtonian fluids.

The above theory has been presented for the components and methods implemented in SLOT 2.0. A comprehensive review of the available methods for modelling pressure losses in pipes and fittings was carried out as part of the WWM research program ([17], [18] and [19]). The Hooper 2K method was chosen for fittings since it was able to model both the laminar and turbulent regimes without the need to determine the critical point, due to the accuracy of the results and the large availability of data for various different fittings.

5.5 Pump Start-Up Pressure

The static yield stress, τ_0, defines the minimum shear stress which must be exceeded for fluid motion to occur. This can be converted, using Equation (9), to a pipe pressure which must be exceeded for fluid motion, and summing the contributions for all pipes (*p*) in the system gives the Startup Pressure:

$$P_{startup} = \sum_{p} \frac{4L_p}{D_p} \tau_0 \tag{42}$$

Note that it is the frictional component of the overall pressure which must exceed the Startup Pressure. Note also that $P_{startup}$ contains no contribution from fittings, so it is not a conservative figure, but gives a rough estimate for the frictional pressure loss required across the system for fluid motion.

5.6 Pump Scalings

5.6.1 Affinity Laws

For Rotodynamic pumps (centrifugal, axial or mixed flow type) there are Affinity Laws which describe how the pump head and flow rate change for a change in impeller speed [20]. For a specific pump with fixed impeller diameter with initial head H_1, flow rate Q_1 and speed N_1, the head H_2 and flow rate Q_2 for a new pump speed N_2 may be found from:

$$\frac{Q_2}{Q_1} = \frac{N_2}{N_1}, \quad \frac{H_2}{H_1} = \left(\frac{N_2}{N_1}\right)^2 \tag{43}$$

These similarity rules assume that the pump efficiency is the same for the changing speed, which is not true in general. SLOT 2.0 implements the above scalings for rotodynamic pumps, scaling the pump curve relative to the rated speed for a different pump speed. For positive displacement pumps the scaling is not applicable.

Note these scalings only apply to Rotodynamic pumps and not to those of a Positive Displacement type.

5.6.2 Pumps in Parallel and in Series

Parallel

When two (or more) pumps are arranged in parallel their resulting performance curve is obtained by adding the pump flow rates at the same head as indicated in the Figure 11 [21]. Pumps in parallel share the same suction and inlet conditions and are used to provide larger volumetric flow than one pump can handle alone. Note the effect on the operating point, going from Point 1 for a single pump to Point 3 for two pumps in parallel following the system curve, increasing the flow rate but not as much as expected with the same head (Point 2).

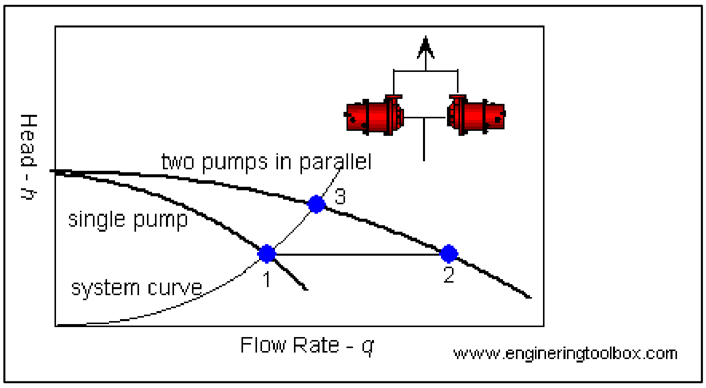


Figure 11 – Pumps in Parallel

<u>Series</u>

When two (or more) pumps are arranged in series their resulting performance curve is obtained by adding the pump heads at the same flow rate as indicated in Figure 12 [21]. Pumps in series are used to overcome larger system head loss than one pump can handle alone. The effect on the operating point sees an increase in the head (Point 1 to 3) but not as much as expected for the same flow rate (Point 2).

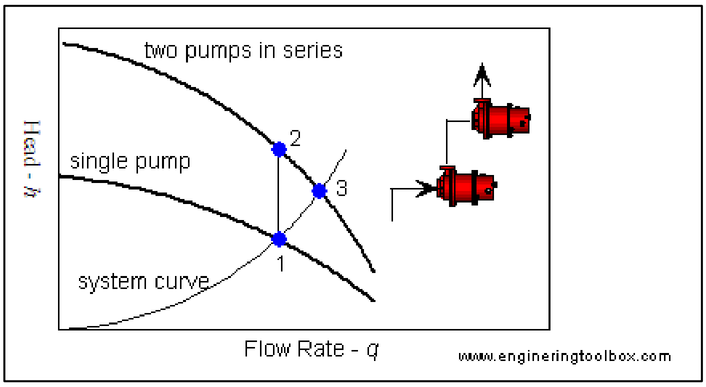


Figure 12 – Pumps in Series

6 Validation

SLOT has been developed to update the TR185 based methods with more up-to-date, accurate and meaningful analysis and calculations. All of the methodology behind SLOT has been presented in Section 5 with references which detail the experimental justification for the methods and formulae used. A comprehensive review of the available methods for modelling pressure losses in pipes and fittings for Newtonian and non-Newtonian fluids was carried out as part of the WWM research programme (CR 8172 [17], CR 8255 [18] and CR 8268 [19]) and the most appropriate methods chosen for SLOT.

In addition to the theoretical grounding behind SLOT, the following validation was carried out.

6.1 TR185 vs SLOT

The pressure losses obtained using SLOT were compared with TR185 with identical inputs (sludge flow rates, Herschel-Bulkley sludge rheology model parameters) for the same components (straight pipe, 90°elbow (long radius), both of diameter 0.3 m) and for the following sludge types:

- Sludge A: Primary poly-thickened (7% DS), laminar flow.
- Sludge B: Digested (3% DS), laminar & turbulent flow.
- Sludge C: Digested (6% DS), laminar & turbulent flow.

The ratio of ΔP_{SLOT} to ΔP_{TR185} is plotted against pipe velocity for:

- The straight pipe in laminar flow in Figure 13.
- The straight pipe in turbulent flow in Figure 14.
- The 90°elbow in laminar flow in Figure 15.
- The 90°elbow in turbulent flow in Figure 16.

Frictional losses calculated using TR185 were found to be universally higher than those from the more rigorous SLOT when identical inputs were used. The largest differences related to turbulent compared to laminar losses for the straight pipe and to the fitting (90° bend) compared to the straight pipe losses overall.

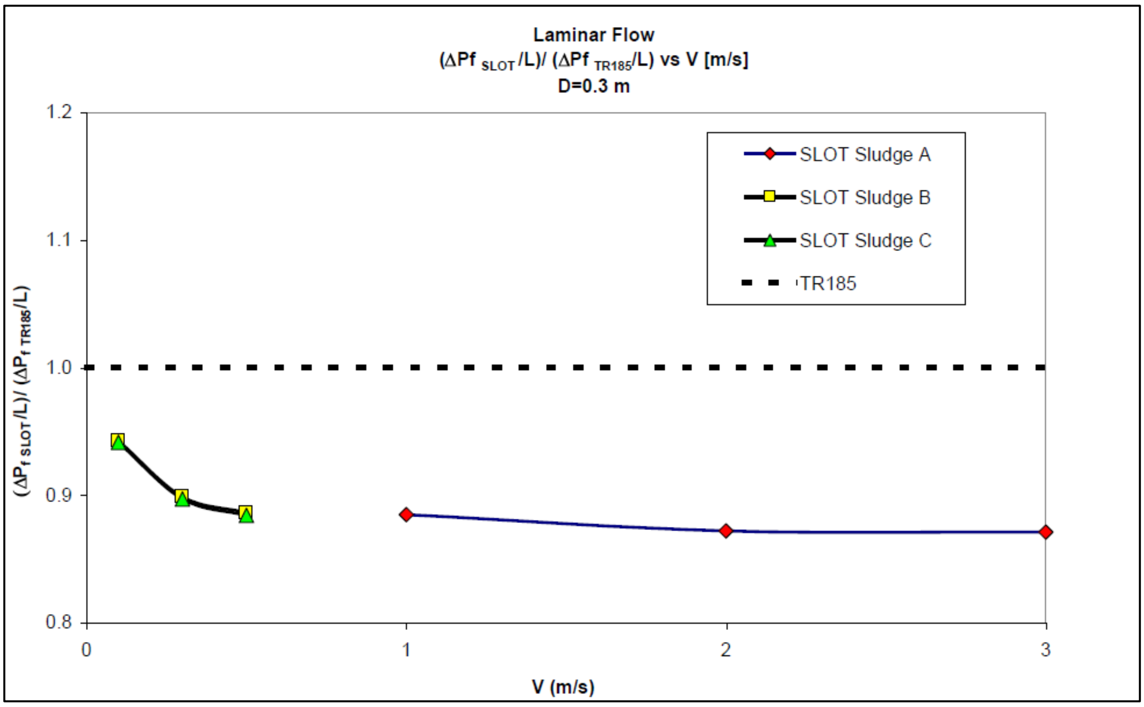


Figure 13 – Straight Pipe, Laminar Flow

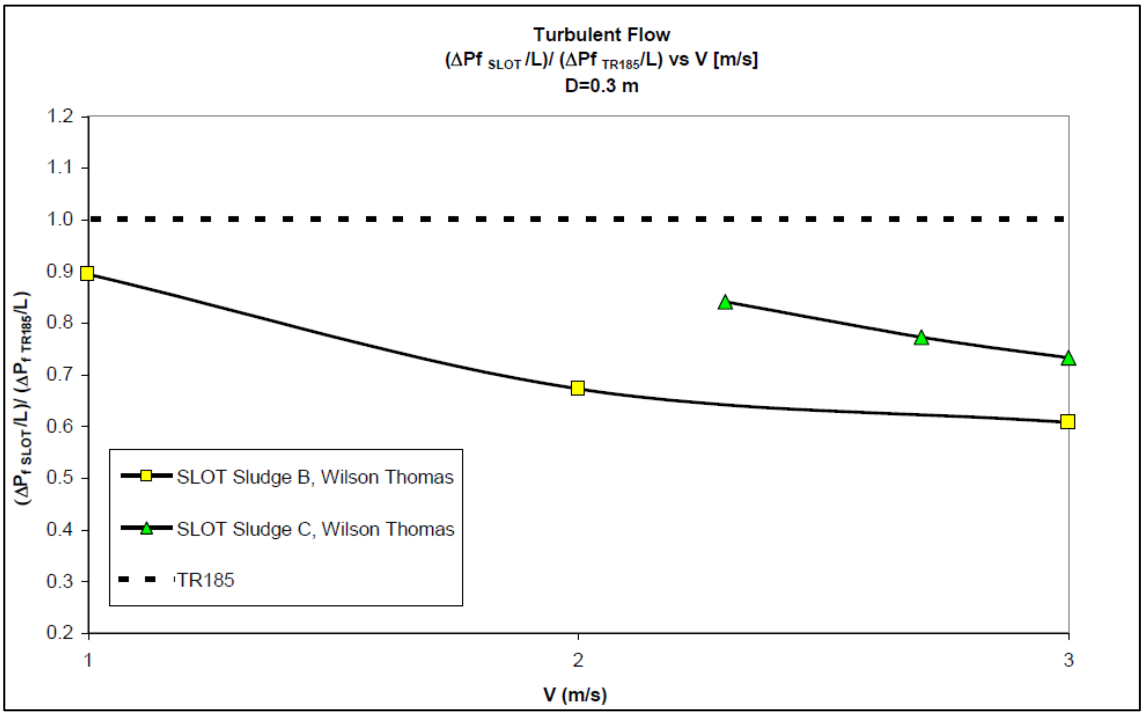


Figure 14 – Straight Pipe, Turbulent Flow

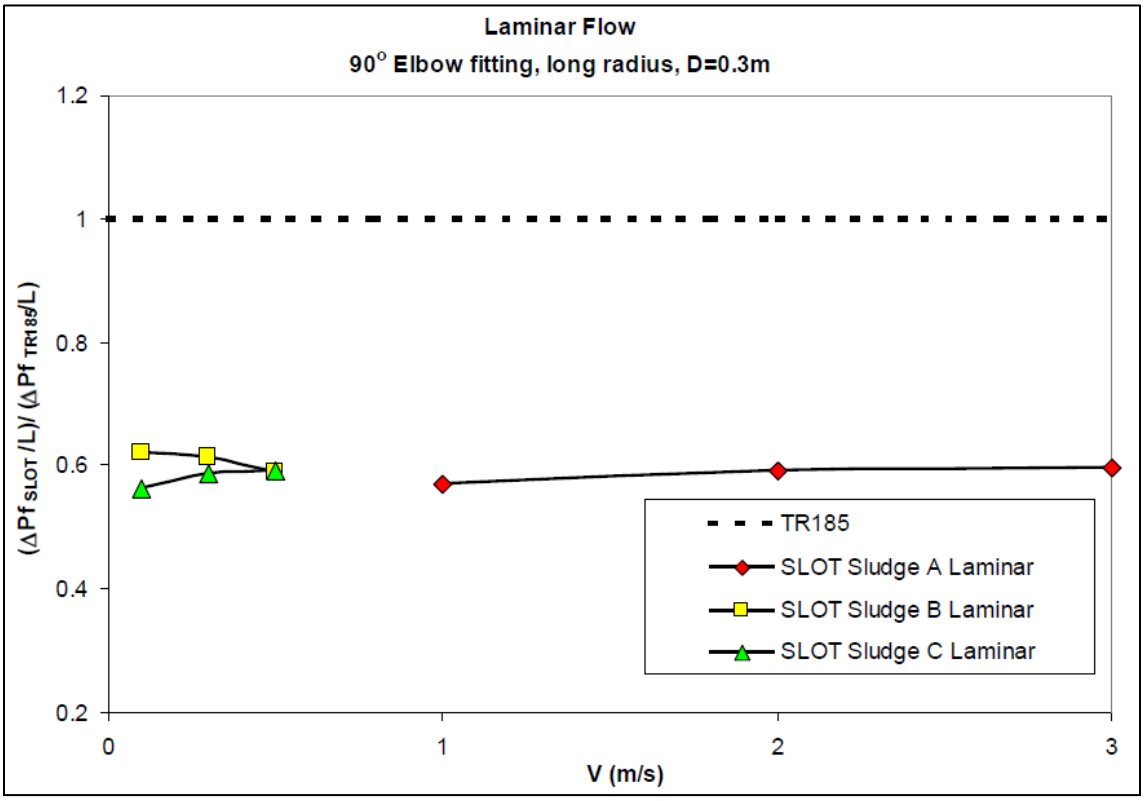


Figure 15 – 90° Elbow, Laminar Flow

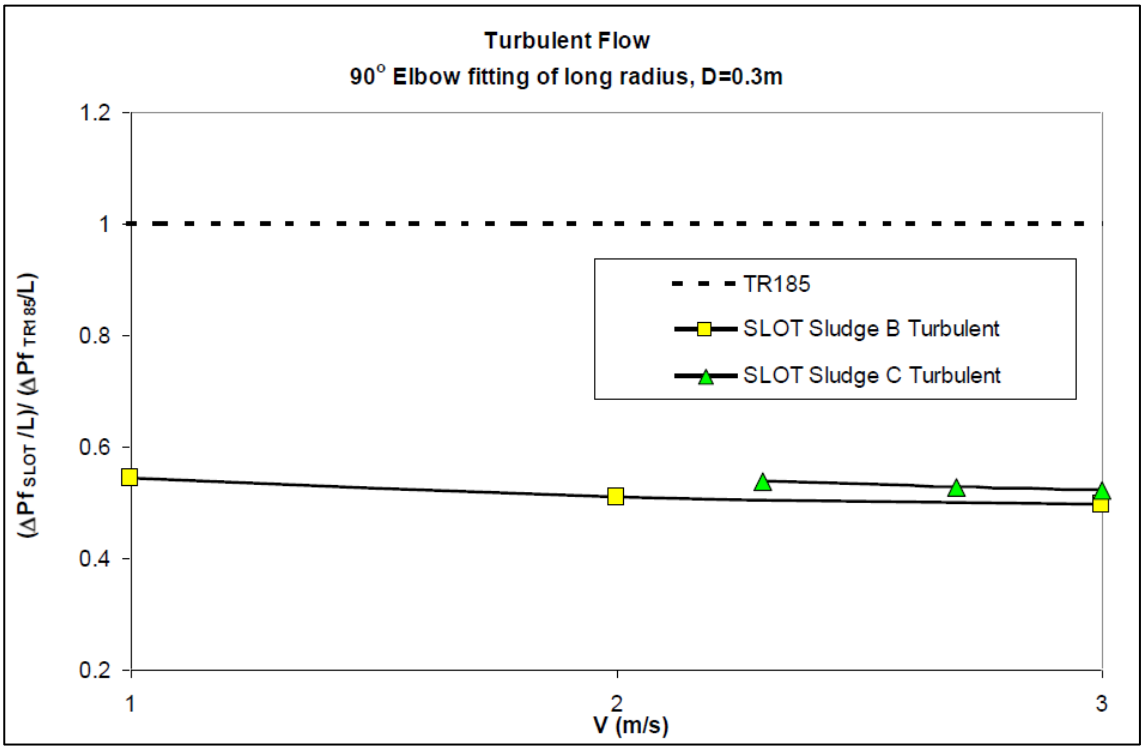


Figure 16 – 90° Elbow, Turbulent Flow

6.2 Llanant WWTW

A validation exercise was carried out based on the Llanant Waste Water Treatment Works, using primary thickened sludge data (7.9%DS). In this exercise the sludge flow achieved in practice was compared with that predicted using SLOT.

The pipe system consisted of:

- 7 m of 250 mm diameter pipe featuring 1 standard bend and 1 gate valve.

Followed by:

- 2.5 m of 200 mm diameter pipe featuring 5 standard bends, 1 gate valve and 1 reducer (200 to 120mm).

The sludge properties were determined using the SRDB Correlation Calculator with the relevant Herschel-Bulkley fluid parameters. The system curve for the pipe system and fluid was compared to the Flygt Sludge pump curve and the operating point was found to be within the pump operating range found in reality (as shown in Figure 17).

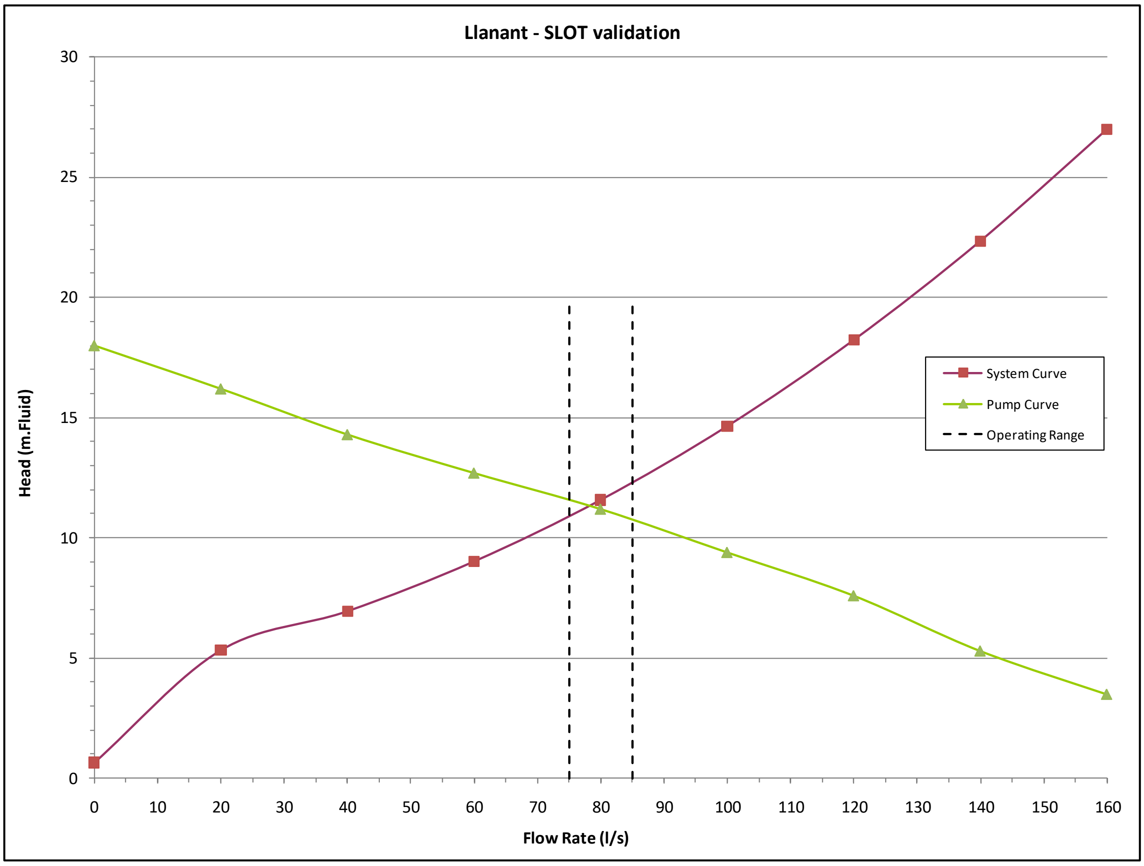


Figure 17 – SLOT Validation: Llanant WWT

6.3 BHR Test Rig

A validation exercise was carried out by experimental testing at Framatome BHR. The test rig consisted of:

- 13.4 m of 1.5” or 4” horizontal and vertical pipe sections.
- Various fittings: valves, elbows, contractions, expansions, tees.
- Pump: ITT Lowara – FHS 80-250/370.

Different non-Newtonian fluids were tested, Carboxymethyl Cellulose (CMC) and Rhodopol, with the following measured rheological properties:

Fluid Description	Flow Model	τ [Pa]	K [Pa.s^n]	n
CMC (2%)	Power Law	0	11.1	0.36
CMC (2.5%)	Power Law	0	5.1	0.42
Rhodopol (1%)	Herschel-Bulkley	2.9	10.6	0.19

Table 7 – Test Fluid Model Parameters

The experimentally measured system pressure loss curves were compared with SLOT and TR185 predictions. The comparisons are shown for the CMC fluids in Figure 18 and Figure 19 and for Rhodopol in Figure 20. The SLOT results match the test results well and are consistently closer than the TR185 results, with lower pressure losses shown for the same flow rate.

Together with the TR185 vs SLOT comparisons shown in Section 6.1, this shows that pump specification using TR185 could result in over-sizing and the use of SLOT should produce more accurate results, enabling a possible reduction in capital/operating costs and carbon footprint.

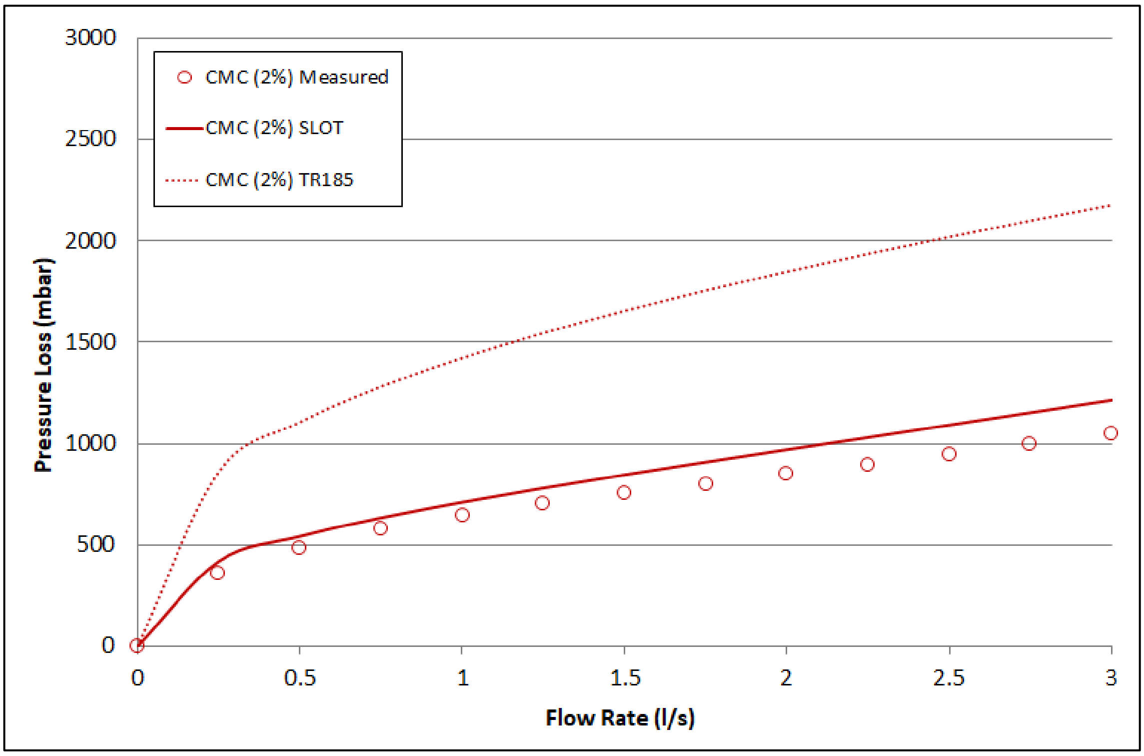


Figure 18 – SLOT Validation: Power Law Fluid (CMC 2%)

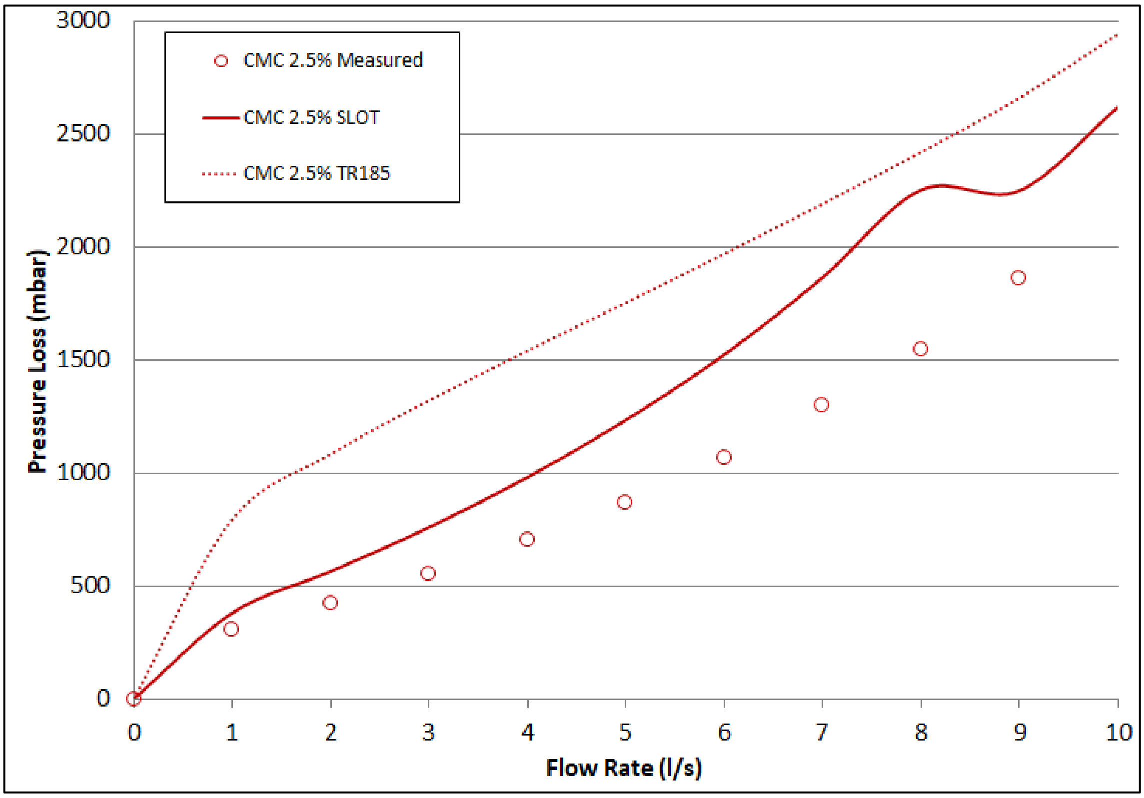


Figure 19 – SLOT Validation: Power Law Fluid (CMC 2.5%)

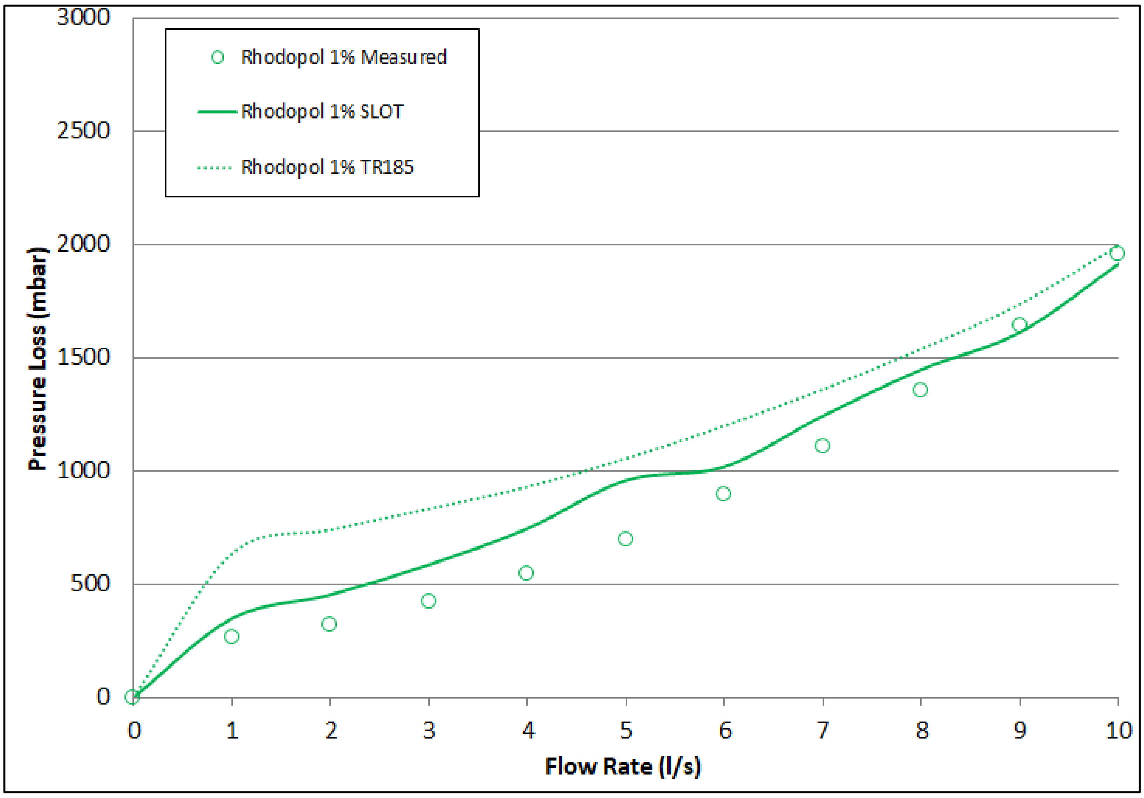


Figure 20 – SLOT Validation: Herschel-Bulkley Fluid (Rhodopol 1%)

7 Support Levels

The different levels of support provided by Framatome BHR in dealing with customer issues with SLOT 2.0 are as follows:

Priority Level	Customer Issue	Customer Action	Framatome BHR Response
Priority Level 1	Project/time sensitive request for support in achieving a given design solution or software running issue.	Contact Framatome BHR by telephone to speak with one of the SLOT 2.0 champions for advice and support to achieve the desired design outcome.	Provide telephone support subject to a selected support plan within two hours during a working day of 09:00 to 17:00.
Priority Level 2	Moderate level request for support or advice on how to operate/configure/achieve a given software function.	Contact Framatome BHR by telephone or e-mail to log the request.	Log the request within the same calendar day and provide a response by telephone or e-mail the next working calendar day.
Priority Level 3	Low level request for support or advice on how to operate/configure/achieve a given software function.	Contact Framatome BHR by telephone or e-mail to log the request.	Log the request within one to three days and provide a response by telephone or e-mail within 5 days of receiving the request.
Priority Level 4	Requests or suggested changes to SLOT 2.0 to improve its functionality or address specific operating issues.	Log the request with Framatome BHR via e-mail.	All requests and suggestions for software improvements are considered in subsequent iterations. Each suggestion will be answered to the requester within four calendar weeks.

Email: slot2.0@framtatomebhr.com

URL: https://slot.framatomebhr.com/

8 About the Authors

Dr Mick Dawson

Mick heads up the Framatome BHR consulting team and is a Chemical Engineer with more than 30 years managerial, technical and commercial experience. Mick managed the Water and Wastewater Mixing (WWM) research consortium which pioneered the application of chemical engineering mixing research principles to specifically water industry applications. He has managed and worked on consultancy projects and audits involving all aspects of mixing across water, wastewater and sludge processing. Mick regularly presents seminars and webinars on mixing in the water industry and is author of Mixing in Water and Wastewater Treatment chapter in 'Advances in Industrial Mixing: A Companion to the Handbook of Industrial Mixing' (2015).

Dr Nick Brown

Nick leads Framatome BHR's Modelling and Simulation team and has particular experience in the water, oil and gas and nuclear industries. This experience made him the ideal person to lead the transition and validation process, converting SLOT into SLOT 2.0.

He has extensive fluid engineering expertise, particularly in the fields of incompressible flows (internal and external), drag and valve coefficient determination, multiphase flows, moving components, fluid structure interaction (FSI), compressible flows (ideal and real gas formulation) and heat transfer. He also has experience in structural assessment, fatigue, surge analysis and engineering design.

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