FLOWNEX®
SIMULATION ENVIRONMENT

CASE STUDY

COALESCING FILTER SIZING AND LIFE CYCLE ANALYSIS USING RATED AND SPECIFIED PRESSURE LOSS COMPONENTS

This case study discusses the sizing of a coalescer filter and demonstrates its fouling life cycle analysis using a Flownex® model which implements two new pressure loss components:

- A rated pressure loss component.
- A specified pressure loss component.

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Challenge:

The main challenge is the sizing and life cycle analysis of a typical coalescing filter. To simplify the Flownex model and assist with the analysis of the system performance, two new pressure loss components have been developed and are also presented in this case study.

Benefits:

Although not overly complicated, the design and lifecycle analysis of a filter system has a few interesting aspects that need to be highlighted. The two new components specifically developed to assist with this analysis should prove useful to other Flownex users by simplifying the specification of typical pressure losses in complex networks.

Solution:

A complete filter life cycle analysis is presented which may be applied to other similar filtration systems in Flownex networks. Two simple compound components have been developed and are discussed and demonstrated in this case study.

"The ability to simplify complex systems into a few basic components, coupled with Flownex's designer and sensitivity analysis capabilities, offers the design engineer a tool of incredible power and flexibility."

Hannes van der Walt
Principal Thermal Engineer
Gasco (Pty) Ltd

Introduction

In the oil and gas industry, Flownex is often used to build complex gas flow networks with the purpose of determining pressures, temperatures and velocities at any point, and pressure losses of certain components or groups of components, as well as the system as a whole.

As such, situations often arise where the pressure loss of a component or network area is known at certain conditions (at a certain flow, a certain pressure and a certain temperature for a certain gas) but calculations have to be performed at other conditions. It is for this specific purpose that the *Rated Pressure Loss* component was developed and is presented in this case study.

> "The operational life cycle of such a coalescing filter is more complicated than it may at first appear and is presented and discussed in this case study."

A typical application of the *Rated Pressure Loss* component is a gas coalescing filter, which serves the purpose of removing solids and liquids from the gas, and as such will become increasingly fouled, resulting in increasing pressure losses. The operational lifecycle of such a coalescing filter is more complicated than it may at first appear and is presented and discussed in this case study. Coalescing filters also serve to remove liquids from the gas flow, however, the detail of the liquid removal process is outside of the scope of this case study and is not considered in detail.

Similarly, the user often wants to specify a constant pressure loss for a component or area, typically during the design phase when pressure loss quotas are allocated to specific components or areas. The *Specified Pressure Loss* component was developed for this purpose and is also presented in this case study.

Gas Coalescing Filter Operation

Coalescing filters vary substantially in size and design. A reasonably large example of an upright coalescing filter used in a gas-fired power station gas conditioning skid is shown in Figure 1. This specific coalescing filter is fitted with 29 Pall Seprasol® cartridge elements offering 9.66 m^2 of filtration area and is designed to handle flow rates of up to 39.2 kg/s at a maximum inlet pressure of 15306 kPag and a clean filter pressure drop of 13.1 kPa.

Figure 1: Typical Natural Gas Coalescing Filters in a Gas Turbine Power Station.

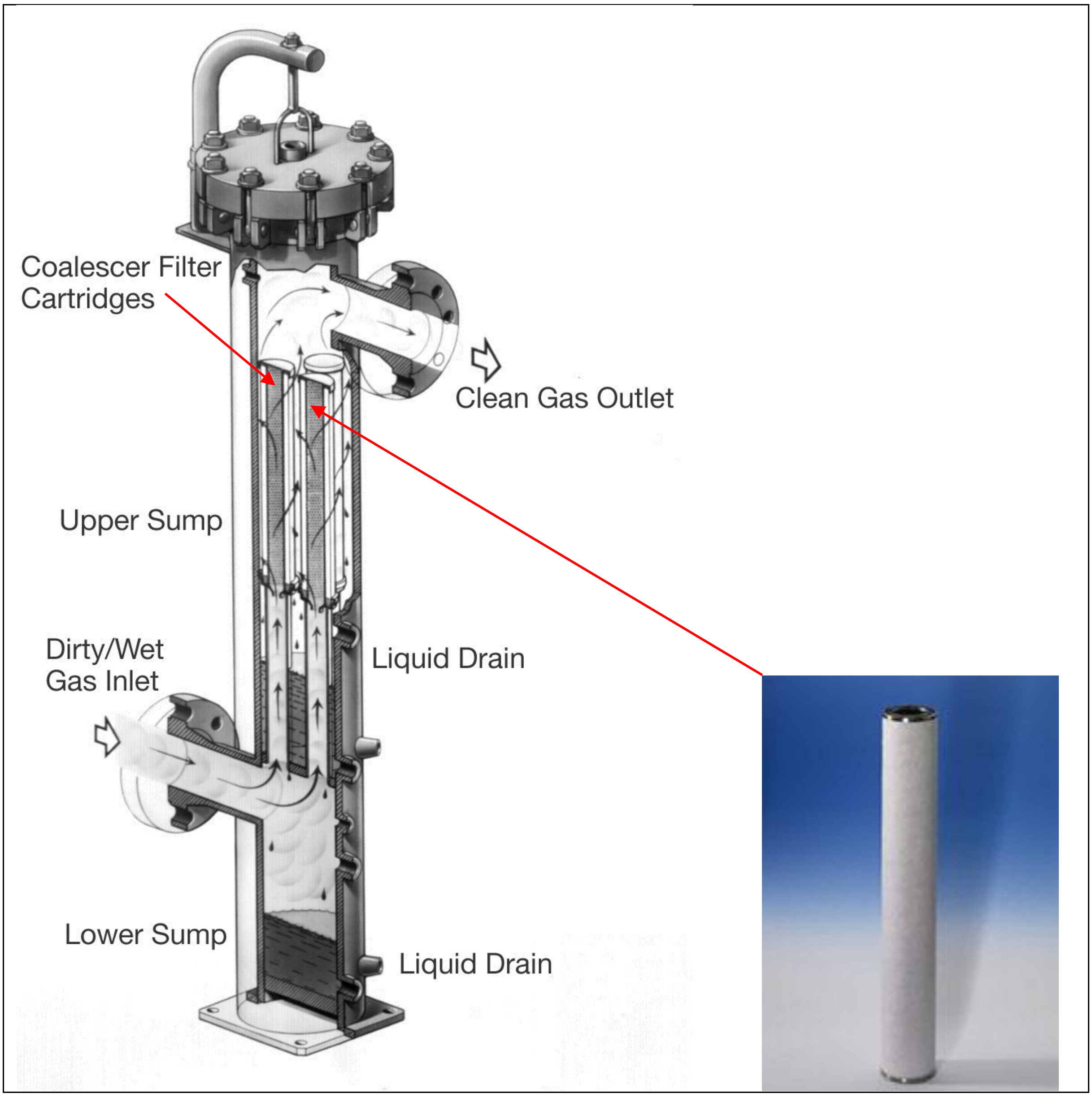


Figure 2: Operation of a Pall® Coalescing Filter.

Gas coalescing filters operate by passing the gas through filter cartridges to trap solids and liquids. Figure 2 shows the typical operation of a coalescing filter as well as a single Pall Seprasol® filter cartridge. Gas enters the coalescing filter approximately in the bottom third with the vessel diameter much larger than the supply line diameter. The consequent reduction in velocity is enough to allow most liquid droplets and any larger solids to drop out of the upwards flowing gas stream and be collected in the lower sump from where it may be drained in intervals.

The gas then flows towards the upper section of the vessel where it enters the filter cartridges from the inside, leaving any solids behind as it flows through to the gas outlet as shown. Liquid droplets that were not removed via gravity in the bottom section of the vessel due to their small size, will also be coalescing in the fibres of the cartridges and will be collected in the upper liquid sump to be drained in intervals. The number of coalescing filter cartridges housed in the filter vessel depends on the following:

- the maximum gas flow rate;
- the expected solid and liquid material loading;
- the required clean filter pressure loss; and
- the required mean time between replacement (MTBR) of the filter cartridges.

During the early plant design phase the exact number of filter cartridges required may not be known, however, the pressure loss characteristics of a single cartridge is readily available from Pall®. The *Rated Pressure Loss* component simplifies the design process by enabling the Flownex user to specify the pressure loss *rating* of a single filter cartridge (or a number of cartridges) and then scale the elements to larger or smaller sizes according to an area ratio. Furthermore, different flow conditions such as pressures, temperature and flow rates may then be used once a filter has been *rated*.

An important part of filter design is to consider the operational life cycle of the unit with specific emphasis on the mean time between replacement (MTBR) and bursting pressures of the cartridges under certain conditions. To assist with this, the *Rated Pressure Loss* component allows the user to apply fouling to the cartridges, resulting in increases in pressure losses.

Implementing the Rated Pressure Loss Compound Component

The *Rated Pressure Loss* component is based on Flownex's General Empirical (GE) relationship. The GE component is a very simple element that is often used to relate flows to pressure losses according to the following simple relationship (refer to the Flownex Help):

$$\Delta P_0 = C_k \, \rho^{\beta} \, Q^{\alpha}$$

Equation 1

where

ΔP_0 is the total (stagnation) pressure loss [Pa]
C_k is the pressure loss coefficient
ρ is the mean fluid density [kg/m^3]
Q is the fluid volume flow rate [m^3/s]
α is the proportionality constant between pressure loss and velocity and is taken as 2 since the pressure loss is proportional to the square of the velocity
β is the proportionality constant between pressure loss and density and is taken as 1

The above equation is expressed in terms of volume flow, but it may be reorganised in terms of mass flow as follows:

$$\Delta P_0 = C_k \frac{\dot{m}^2}{\rho}$$

Equation 2

where

$\dot{m}$ is the fluid mass flow rate [kg/s]

Given a known or required pressure loss, density and flow rate (mass flow or volume flow), the required pressure loss coefficient may be calculated:

$$C_k = \frac{\Delta P}{\rho\, Q^2} \quad \text{and} \quad C_k = \frac{\Delta P\, \rho}{\dot{m}^2}$$

Equation 3

Note that these equations account for variations in density, and hence pressure and temperature, but they do not account for variations in viscosity. Since viscous effects are very important in pressure drop calculations, the *Rated Pressure Loss* component should only be *rated* and then *scaled* with fluids (gases in this case) of similar viscosity.

These two equations have been implemented in a script and connected to a GE component via a data transfer link (DTL) to create the *Rated Pressure Loss* component.

Specify Pressure Loss Rating	True
Specified Loss Coefficient (Ck)	5.000
Area Ratio (Actual / Rating)	1.000
Fouling	0.000 %
Rating Flow Option	Mass flow
Rating Mass Flow Rate	7200.0 kg/h
Rating Volume Flow Rate	1066.1 m³/h
Rating Density	6.754 kg/m³
Rating Pressure Loss	6.743 kPa
Loss Coefficient (Ck)	11384.893
Pressure drop excluding elevation	6.741 kPa

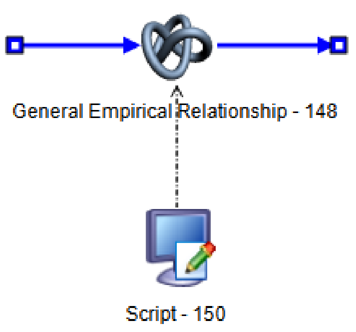


Figure 3: Implementation of the *Rated Pressure Loss* compound component using a GE component and a Script.

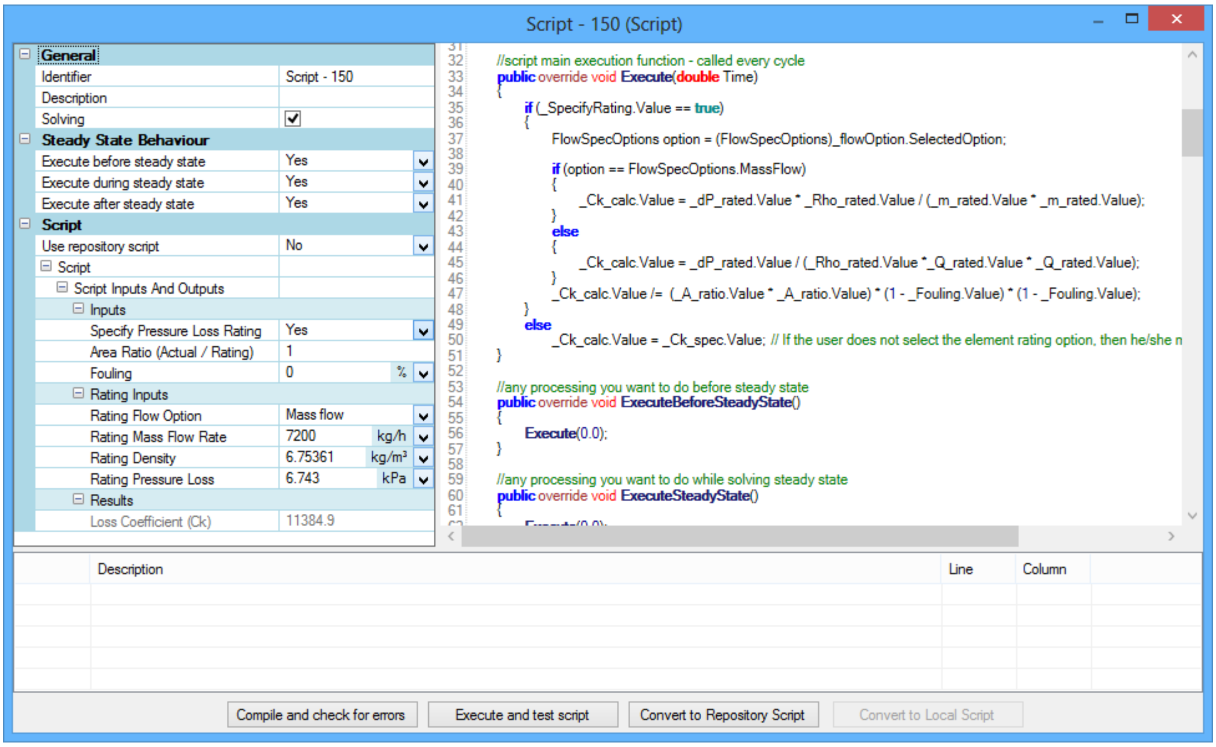


Figure 4: Implementation of the two forms of Equation 3 in the Script.

As shown in the script above, both forms of Equation 3 are implemented in the inner-most if-else statement. The outer-most if-else statement allows the user to either specify rating parameters (see the rating input fields above) or directly specify the pressure loss coefficient C_k.

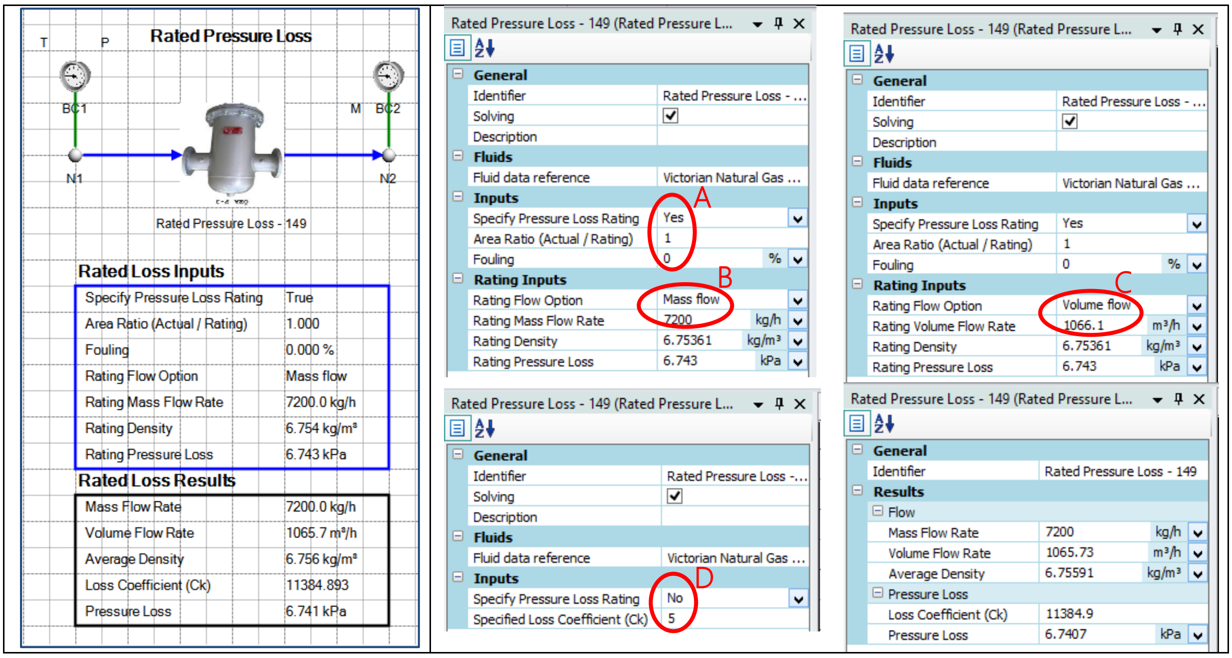


Figure 5: Using the Rated Pressure Loss Component.

As shown above (left), the *Rated Pressure Loss* component is a simple compound component that is used in a network like any other flow component. The input and result fields are shown on the right in Figure 5. The user may specify a loss rating (option A) which then requires the specification of an area ratio as well as several rating inputs as shown. The area ratio is the ratio of the actual filter element surface area to the surface area of the filter for which rating data is supplied. Typically this area ratio may be used as a number ratio of actual to rated filter cartridges.

Filter pressure loss rating data consists of a flow rate (mass flow or volume flow as selected by options B or C), a reference density, which is the gas density applicable to the rating flow, and the pressure loss, which would be measured for a clean filter at the rating conditions.

For fouling studies, the user may specify a level of fouling (the third field in circle A) which is only valid between 0% and 99% and simply serves to reduce the filter area proportionally.

Lastly, the user may opt not to specify rating data and simply specify the loss coefficient C_k directly as shown by D.

Implementing the Specified Pressure Loss Compound Component

This compound component is also based on the same Flownex GE element but only implements the first form of Equation 3. It allows the user to specify a required pressure loss for a specific component or group of components regardless of the pressure, temperature and flow rate. The *Specified Pressure Loss* component script will then use the actual volume flow rate and density to calculate an appropriate pressure loss coefficient C_k to result in the required component pressure loss. Furthermore, the user may also specify a required or desired flow velocity. The script will then calculate a required flow area to satisfy that requirement.

Loss Specification Option	Pressure Loss
Required Pressure Loss	30.000 kPa
Required Velocity	15.000 m/s
Volume Flow	0.243 m³/s
Average Density	8.216 kg/m³
Required Area	0.016 m²
Loss Coefficient (Ck)	61619.661
Pressure drop excluding elevation	30.000 kPa

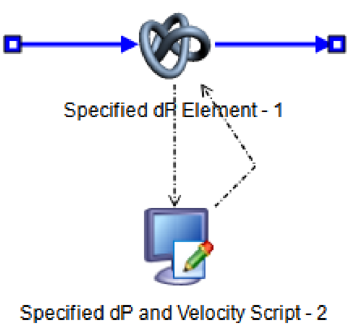


Figure 6: Implementation of the *Specified Pressure Loss* compound component using a GE component and a Script.

This component has one more handy capability. As discussed above, the user may specify a pressure loss for the current flow conditions which will result in an appropriate loss coefficient being calculated. The user may then change the *Loss Specification Option* to *Constant Loss Coefficient*. The component will then maintain the same loss coefficient regardless of the flow conditions. This allows the component to be used in situations where a specific pressure loss is known at a specific flow condition. The component is then "calibrated" and then switched to a constant loss coefficient model, so that the pressure loss at other flows, pressures and temperatures may be calculated. This gives the *Specified Pressure Loss* component some of the rating capabilities of the *Rated Pressure Loss* component albeit in a simpler, yet less flexible manner.

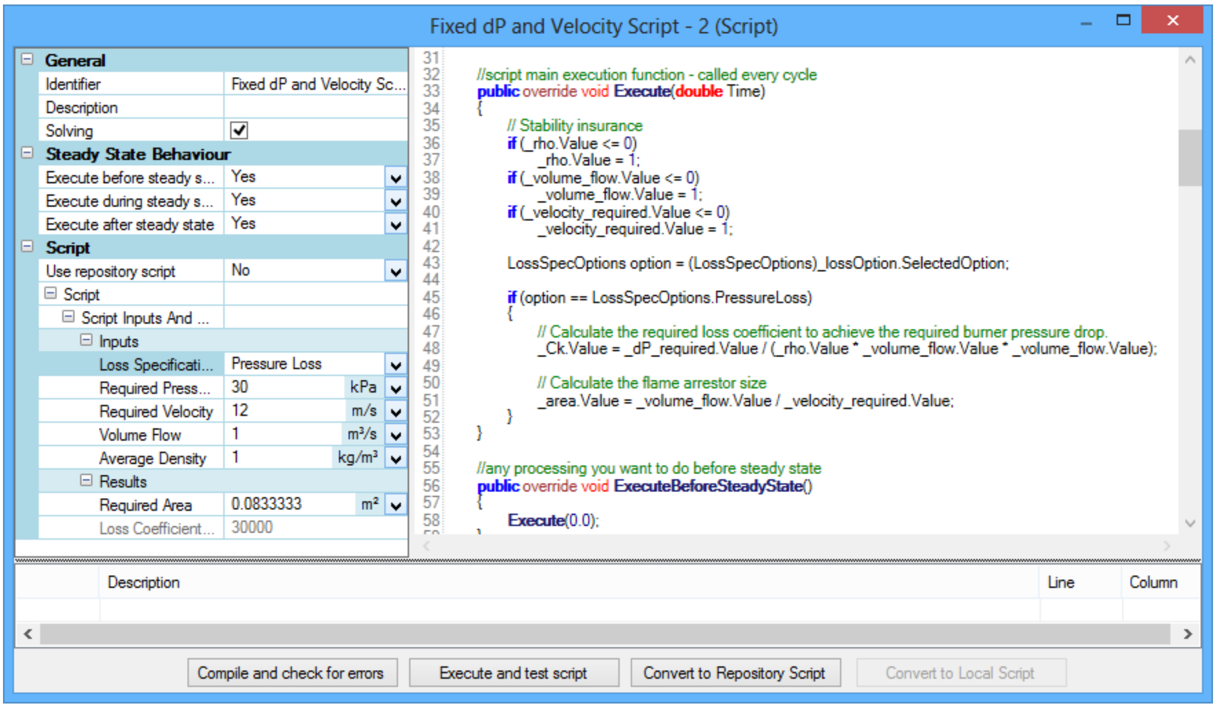


Figure 7: Implementation of the two forms of Equation 3 in the Script.

As shown in Figure 7 above, the loss coefficient and area are only calculated and updated to the GE component when the *Pressure Loss* option is selected.

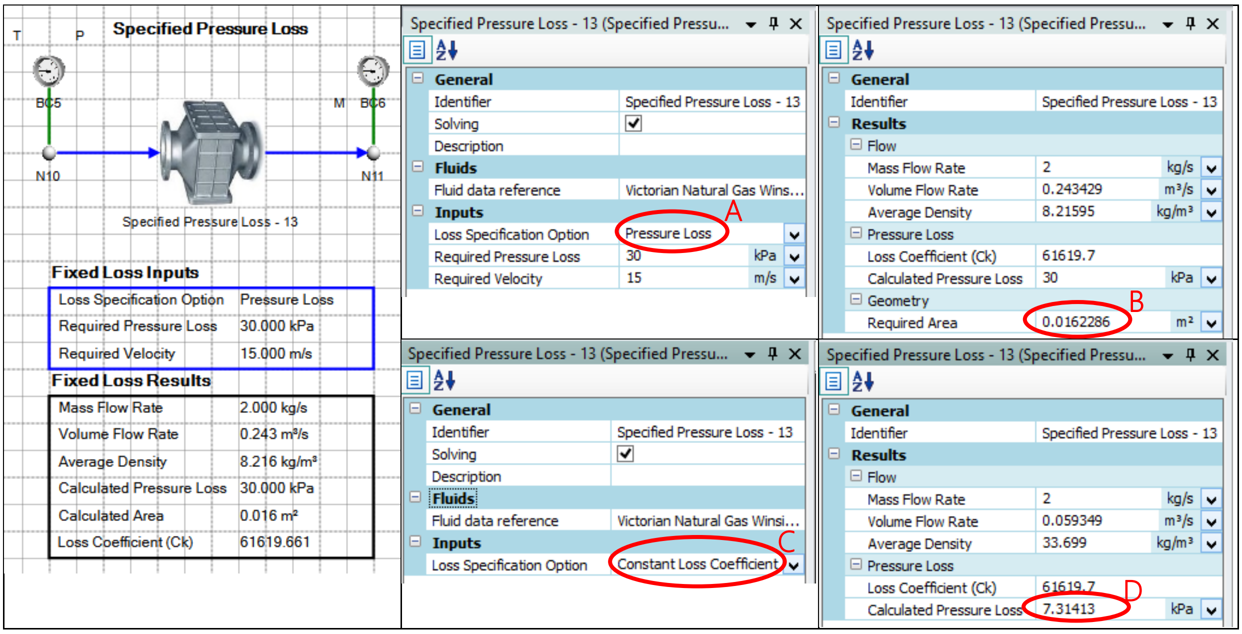


Figure 8: Using the Specified Pressure Loss Component.

As shown above, the *Specified Pressure Loss* component is used in the same way as the *Rated Pressure Loss* component discussed before. The input - and result fields are shown on the right in Figure 8. The user may specify a *Pressure Loss* option (option A) which then requires the specification of the required pressure loss and required velocity. The results will include the required flow area to satisfy the specified velocity requirement (B).

The loss specification option should only be changed to *Constant Loss Coefficient* after the component had been "calibrated" to ensure a valid loss coefficient C_k is assigned to the GE component. With this option selected, the pressure and velocity requirement input fields are removed as well as the required flow area result field. As shown in Figure 8 (D) above, a constant loss coefficient at a supply pressure of 4000 kPag instead of 1000 kPag as before will result in a much lower calculated pressure loss. The *Specified Pressure Loss* component has been used to represent the pressure losses of large sections of the gas conditioning skid.

Case Study: Gas Coalescer Filter Design and Life Cycle

A coalescing filter is to be designed as part of a gas conditioning skid feeding a gas-fired power station. The skid contains the coalescing filter, numerous actuated ball valves, piping, an electric heater and a pressure reducing section. The gas supply to the skid may vary widely in pressure as the upstream piping, which runs for many kilometres, is used as a fuel gas storage buffer. The gas supply temperature may also vary but the flow rate to the gas turbines must be kept practically constant. The minimum fuel gas delivery pressure and temperature are guaranteed by contract and are therefore very critical.

The filter cartridge manufacturer Pall® has advised the following:

- Filter cartridges must be changed out when the measured differential pressure across them has reached 150 kPa.
- The filter cartridges may burst at a differential pressure of 415 kPa. During operation the recommended maximum safe pressure differential is 300 kPa.
- Each coalescing filter cartridge is capable of handling liquid loads of up to 22 ppm_m, hence the number of cartridges may be estimated using the following:

$$N_{cartridges} = ROUNDUP(0.04545 \times ppm_m)$$

where $N_{cartridges}$ is the required number of cartridges, rounded up to the next integer,
ppm_m is the liquid loading in parts per million mass.

- The following clean filter performance characteristics for flowing air were obtained from a prior design:

Table 1: Existing Filter Design Performance Characteristics for Dry Air.

Pressure [kPag]	Temp [°C]	Mass Flow [kg/hr]	Density [kg/m^3]	Vol.Flow [Sm^3/hr]	Number of Cartridges	ΔP [kPa]
800	15	5000	10.8	464	3	28.2
4000	15	5000	50.2	99.6	3	6.1
8000	15	5000	99.5	50.2	3	3.1

The client has provided the following gas conditioning skid performance requirements:

Table 2: Client Design Performance Characteristics for Natural Gas.

Requirement	Unit	Value
Maximum fuel gas flow rate	kg/hr	7200
Minimum fuel gas flow rate	kg/hr	5000
Fuel density (STP conditions)	kg/m^3	0.7443
Maximum supply pressure	kPag	7400
Minimum supply pressure	kPag	1000
Maximum supply temperature	°C	35
Minimum supply temperature	°C	15
Delivery pressure regulator set pressure	kPag	680
Contracted minimum delivery pressure	kPag	550
Contracted minimum delivery temperature	°C	10
Maximum liquid loading	ppm_m	80

A comprehensive Flownex model of the entire skid was developed in order to account for each valve, pipe length, pipe bend, pipe T, coalescing filter and heaters. The purpose of this case study is not to discuss that model but to focus on the coalescing filter unit and the use of the two developed compound components. For completeness, however, Figure 9 is provided below as an overview of the complete network in a clockwise manner starting from the top-left. Fuel gas enters the gas-conditioning skid at the tie-in point at A into the filter skid. The coalescing filter is positioned at point B. The metering skid houses two Coriolis flow meters at C. The heater skid contains two electric heaters in series operation which are shown at D. The regulator skid houses shut down valves and two pressure control valves at E operating in an active-monitor arrangement. The skid outlet is at tie-in point F.

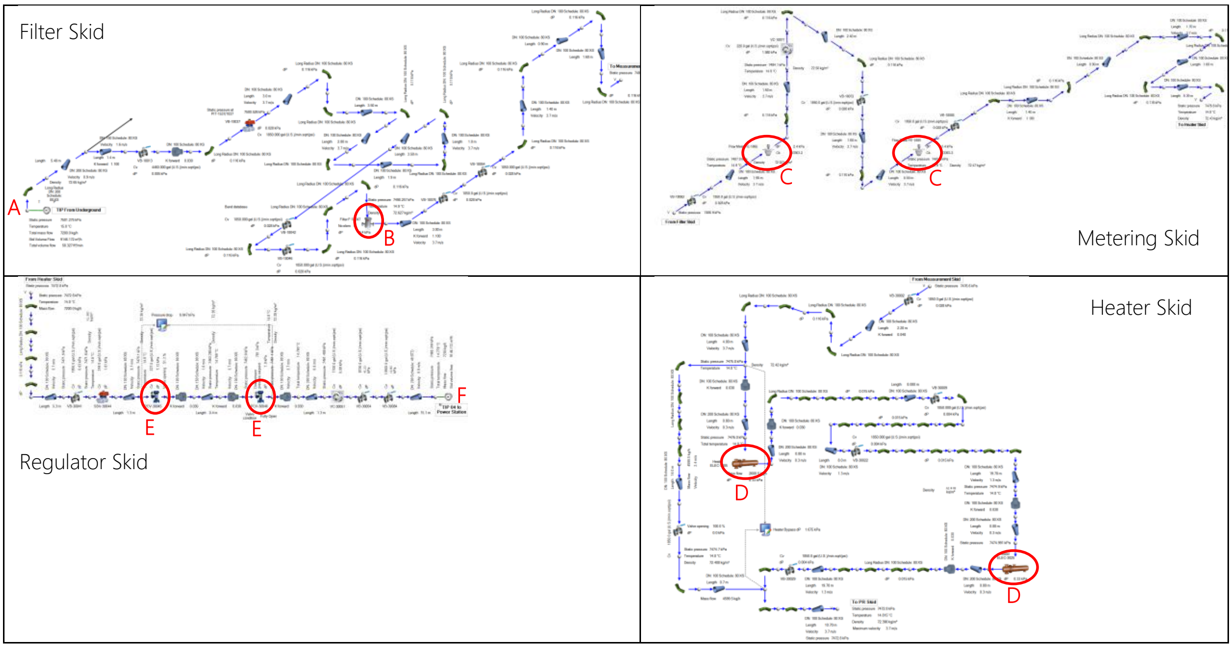
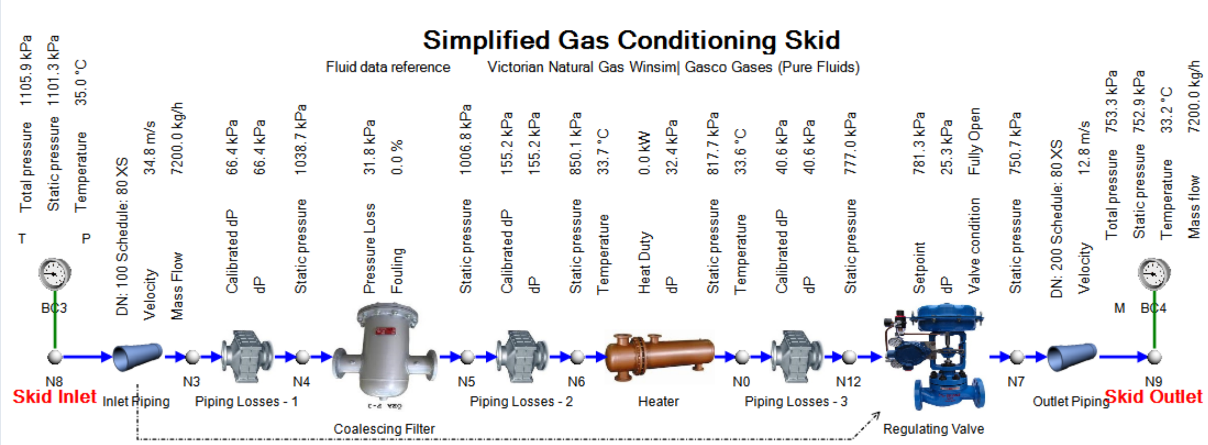


Figure 9: Complete Flownex Model Representing the Gas Conditioning Skid.

Since this case study aims to discuss the application of the *Rated Pressure Loss* component as a coalescing filter as well as investigating the operational life cycle of the filter in practical operation, the network presented in Figure 9 is simplified to only contain the filter component, the heater component and the pressure control valve. Other losses are represented by *Specified Pressure Loss* components for simplicity. This arrangement is shown in Figure 10.



Filter Inputs

Specify Pressure Loss Rating	True
Area Ratio (Actual / Rating)	1.667
Fouling	0.0 %
Rating Flow Option	Mass flow
Rating Mass Flow Rate	5000.0 kg/h
Rating Density	50.200 kg/m³
Rating Pressure Loss	6.100 kPa

Filter Results

Supply Static Pressure	1038.7 kPa
Supply Temperature	34.7 °C
Mass Flow Rate	7200.0 kg/h
Volume Flow Rate	1002.6 m³/h
Average Density	7.181 kg/m³
Loss Coefficient (Ck)	57152.573
Pressure Loss	31.8 kPa

Figure 10: Simplified Flownex Model Representing the Gas Conditioning Skid.

Figure 10 represents actual pressures and pressure losses obtained from the full model. From a pressure drop consideration, there is a very tight margin at low pressure and high temperature (1000 kPag, 35°C) to be able to deliver 550 kPag at the skid outlet. Figure 10 shows the pressures along the gas-conditioning skid for a clean filter. It was determined that only approximately 30 kPa pressure loss can be afforded to the filter under the low pressure, high temperature conditions, resulting in an outlet pressure of practically 650 kPag. This means that there is only a 100 kPa margin for calculation inaccuracies and filter fouling. For simplicity, a margin of 50 kPa (should typically be 10%) will be reserved for calculation inaccuracies which leave approximately 50 kPa for fouling. A design minimum outlet pressure of 600 kPag is therefore targeted.

However, the first step is to verify the details obtained from the filter manufacturer. The information may be checked using a simple network containing just the *Rated Pressure Loss* component as presented in Figure 11. Entering the performance data received from the filter manufacturer as the *Rated Loss Inputs* reveals that the calculated results are in close agreement with the supplied information. It is also shown that the calculated loss coefficient C_k is approximately constant with the value at 4000 kPag close to average. Therefore the rating data at 4000 kPag will be used in the case study. The next step in the design process is to determine the number of cartridges required for this design. There is of course the matter of the liquid loading which often governs this choice. This is normally advised or verified by the filter cartridge manufacturer Pall®, but for this study it is simply estimated using the relationship provided at the start of this section.

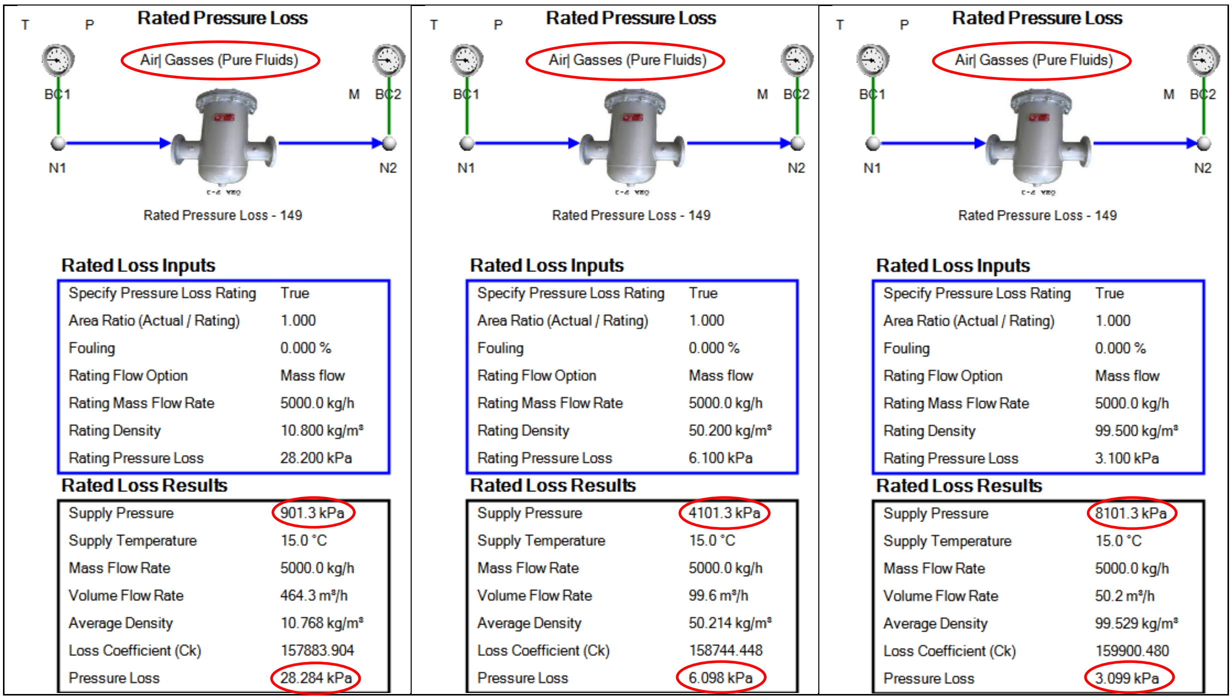


Figure 11: Filter Supplier Performance Data Verification for 800 kPag, 4000 kPag and 8000 kPag Respectively for Air.

Figure 12 shows the expected filter pressure loss for 3 cartridges (Area Ratio = 1.0), 4 cartridges (Area Ratio = 1.333) and 5 cartridges (Area Ratio = 1.667). Aiming for a maximum clean filter pressure loss of 30 kPa suggests the use of a 5 cartridge filter design.

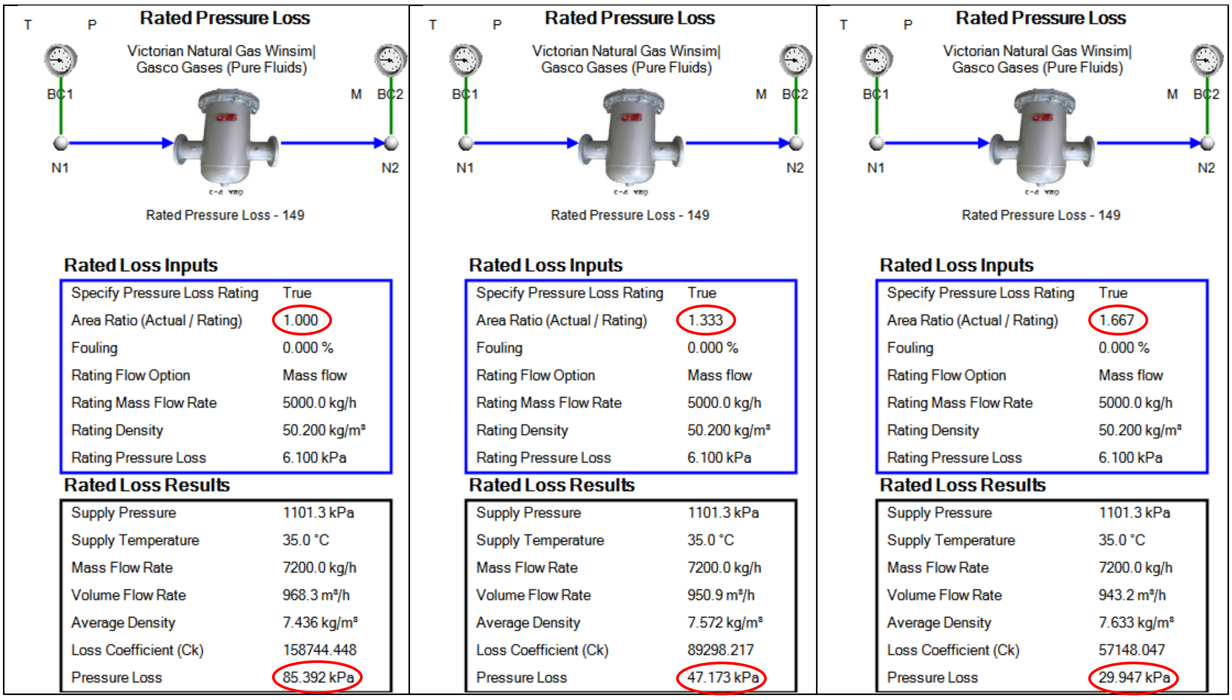


Figure 12: Filter Sizing at Low Pressure, High Temperature for Natural Gas at Design Flow.

For the liquid loading information supplied, the required number of cartridges is:

$$N_{cartridges} = ROUNDUP(0.04545 \times 80) = 4$$

In this case the pressure loss limitation dictates the sizing selection and a minimum of five cartridges must be used.

Using the five-cartridge filter design, the worst case clean filter pressure drop scenario analysis is as shown in Figure 10 above. It is also shown that the regulator is wide open since the pressure at its inlet has dropped below the set point. Higher supply pressures and lower supply temperatures will result in higher pressures at the regulator inlet and consequently the regulator may return to actively regulating the pressure to the set point.

It may appear as if the current design is sufficient, however, before this design is considered acceptable, the operating life cycle of the filter component has to be considered. This means that the impact of pressure and temperature variations as well as fouling have to be considered.

There are three major issues or limitations that need to be considered:

1. *Pressure Constraint System:* Fouling may result in lower outlet pressures, especially for the low pressure, high temperature case. Since there is not much available excess pressure above the design minimum value of 600 kPag (550 kPag + 50 kPa safety margin) at the skid outlet, fouling may cause pressures to drop below the minimum contracted pressure at the skid outlet.
2. *Filter Cartridge Changeout Pressure Limit:* At higher pressures, the system is not pressure constrained at the outlet, and hence fouling appears to become irrelevant. Note, however, that the filter cartridge manufacturer has specified a maximum changeout pressure differential of 150 kPa.
3. *Filter Cartridge Bursting Pressure Limit:* Similarly, as the pressure increases, increasingly heavier fouling appear to be allowable since as the gas density increases, the pressure differential across the filter will decrease for the same physical fouling. However, there is a hidden danger of filter cartridges bursting should the supply pressure reduce whilst the filter cartridges are fouled at high pressures.

These limitations must be tested and the design evaluated using the model presented in Figure 10.

Pressure Constraint System: The filter pressure loss as a function of supply pressure at maximum flow rate is presented in Figure 13. The lower two curves represent clean filter pressure losses for 15°C and 35°C. Since the gas density will be higher at lower temperatures, less pressure loss will be experienced. The upper two curves represent a fouled filter. The level of fouling is determined at the minimum supply pressure of 1000 kPag by adjusting the fouling percentage until a static pressure of 600 kPag at the skid outlet is calculated. The fouling percentage is then kept constant whilst calculating the filter pressure losses for higher supply pressures, i.e. the level of physical fouling is kept constant. The reasoning behind this method is that should the supply pressure drop from a higher pressure to the minimum, the minimum contracted outlet pressure can be guaranteed.

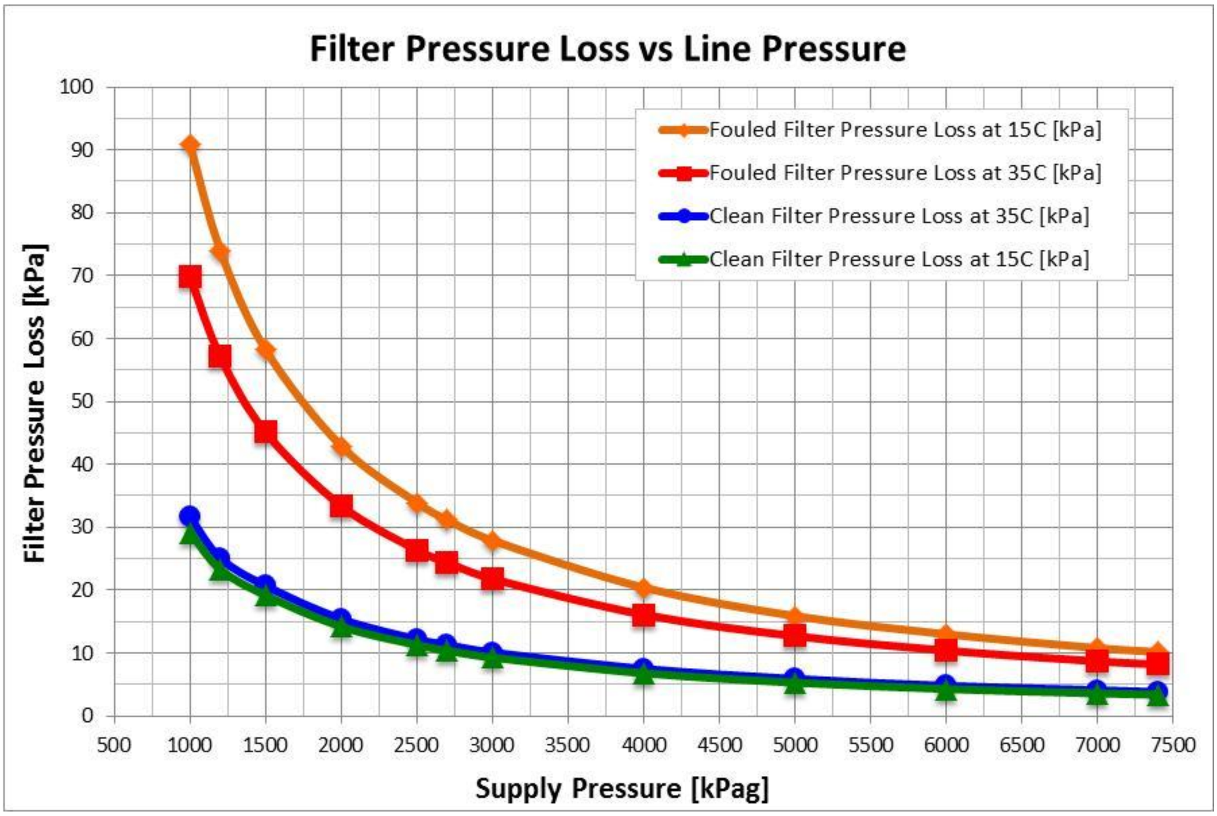


Figure 13: Clean and Maximum Fouled Filter Pressure Loss vs. Supply Pressure and Temperature Ensuring 600 kPag Delivery Pressure (Maximum Flow Rate).

The two groups of curves (clean vs. fouled) plotted represent the minimum and maximum temperatures. It is interesting to note that for the clean filter, the low temperature pressure loss is less than for the high temperature as previously explained, however for the fouled filter, the low temperature pressure loss is higher than for the high temperature. The reason for this is simply that at low temperatures, there are less losses elsewhere in the system, therefore the filter is being fouled more before the 600 kPag design minimum outlet pressure is reached. It is possible therefore that a filter which is fully fouled at low temperature will cause a higher pressure loss should the gas supply temperature increase, causing the skid outlet pressure to fall below the design minimum guaranteed pressure of 600 kPag.

Hence, for a pressure constrained system where the supply pressure may realistically vary between high pressures and the minimum supply pressure such as the one discussed in this case study, it is recommended to allow fouling only between the two inner curves, i.e. the blue and red curves representing the maximum operating temperature of 35°C. This will ensure that the minimum contracted outlet pressure can always be guaranteed.

Filter Cartridge Changeout Pressure Limit: If the upstream control system can guarantee that the supply pressure will not vary suddenly, or that higher pressures could be guaranteed for extended periods of time, then operation may be allowed at filter fouling levels in excess of the *Pressure Constraint System* discussed above. In such circumstances the filter fouling curve will be different. The following figure presents the clean filter (blue) and fouled filter (red) curves from Figure 13 again and then adds three more limit curves for cases where the system will not suddenly become pressure constrained.

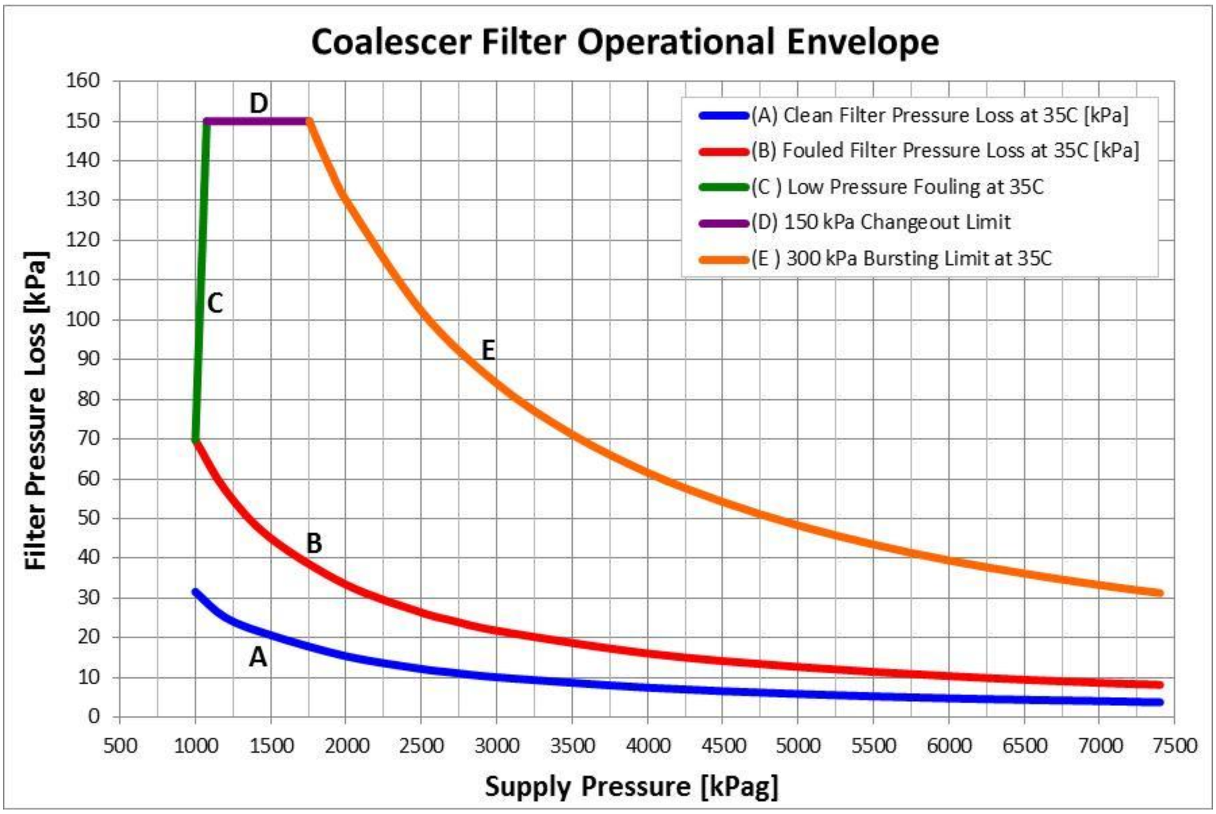


Figure 14: Filter Operational Envelope for Maximum Flow Rate.

As supply pressure increases, there is a larger margin between the minimum guaranteed outlet pressure and the actual (calculated) outlet pressure. This excess pressure may be offset against additional fouling until the filter cartridge change-out limit of 150 kPag has been reached as shown by curve C (green series).

For further increases in supply pressure, the filter is capable of additional fouling by virtue of the reduction in filter pressure loss resulting from the increasing density with increasing pressure. However, the change-out limit of 150 kPag continues to apply and is shown by the horizontal line D (purple series).

<u>Filter Cartridge Bursting Pressure Limit:</u> The filter cartridge bursting limit is represented by curve E (orange series). This curve is calculated in a similar way to the fouling curve B (red series) by solving for the fouling percentage at the minimum contracted supply pressure of 1000 kPag such that a pressure differential of 300 kPa will exist across the filter. This level of fouling is then kept constant when the pressure differential is calculated at higher supply pressures. In essence this curve represents the upper fouling limit at any supply pressure and temperature such that filter cartridges will not burst should a sudden drop of line pressure to the minimum occur.

Discussion

For a pressure constrained system, the amount of fouling allowable between curves A and B above may severely limit the MTBR of the coalescing filter. In such cases it may be necessary to increase the number of coalescing filter cartridges in order to increase the operational “area” between curves A and B.

Furthermore, at flow rates lower than the maximum, the operational envelope presented in Figure 14 must be derated to ensure that the resulting lower pressure losses do not translate into higher levels of fouling, assuming constant density between maximum and actual flow rates:

$$\Delta P_{derated} = \Delta P \times \left(\frac{\dot{m}_{max}}{\dot{m}}\right)^2$$

Summary

Two new compound components have been developed to assist in pressure loss calculations. The *Rated Pressure Loss* component was used to design and analyse the coalescing filter, and the *Specified Pressure Loss* component was used to combine large groups of components in the gas conditioning skid into a single component as presented in this case study. These components are capable of significantly simplifying complex networks and allowing the design engineer to focus on specific areas of interest such as the coalescing filter’s operational life cycle.

The ability to simplify complex systems into a few basic components, coupled with Flownex’s designer and sensitivity analysis capabilities, offers the design engineer a tool of incredible power and flexibility.