Stepwise simulation of vacuum transfer line hydraulics

A stepwise hydraulic calculation determines the pressure profile of a vacuum transfer line by linking the hydraulic model to process simulation results

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When designing a vacuum transfer line, a robust hydraulic model that predicts velocity and a corresponding pressure drop is crucial. A stepwise approach to hydraulic modelling of vacuum transfer lines increases accuracy and enhances the understanding of two-phase fluid behaviour. Vacuum gas oil yield, reliability and operability depend on correct design of the vacuum transfer line.

With the depletion of global conventional oil, refinery feedstocks are becoming heavier and often rely on unconventional heavy oil. Canadian oil sands-derived bitumen — a heavy, unconventional oil — is being increasingly processed in Canadian upgraders to produce synthetic crude oil as part of the crude slate in US refineries. Processing unconventional heavy oil like bitumen is challenging. Unconventional heavy oil is usually unstable and prone to coking at high temperature. To maintain reasonable run lengths, a temperature limit is applied to the heater outlet, which indirectly puts a limit on the heater tube’s inside film temperature.

Design objectives
A typical objective in the design of a vacuum unit is to maximise the yield of vacuum gas oil to improve a refinery’s profitability. The vacuum overhead system, column flash zone, vacuum transfer line and the charge heater have to be optimised as a single system to ensure that design objectives are met during unit operation.

Based on the steam and cracked gas loads, the vacuum overhead system is configured so that a low absolute pressure is ensured in the flash zone to allow the unit to reach target oil vapourisation at an acceptable heater outlet temperature (HOT). A pressure drop in the vacuum transfer line sets the heater outlet pressure (HOP), which in turn determines the HOT by vapour-liquid equilibrium.

The HOT is limited to an acceptable value to avoid coke formation inside the heater coils. A high pressure drop in the vacuum transfer line increases the temperature difference from the heater outlet to the flash zone. Given a fixed HOT, an increased pressure drop in the vacuum transfer line decreases the vacuum gas oil lift in the flash zone, resulting in a lower yield of vacuum gas oil. Therefore, the vacuum transfer line’s hydraulics plays a crucial role in achieving the desired product yields and operational reliability.

A study showed that one extra kPa added to the total pressure drop of a transfer line reduces the gas oil yield by about 0.2 vol%. For a refinery with a 100 000 bpd throughput, each kPa of pressure drop in the vacuum transfer line implies a significant loss of revenue. From a process design point of view, the pressure drop in the vacuum transfer line should be as small as possible to maximise the yield of vacuum gas oil. This usually leads to a large transfer line and increased heater passes, resulting in significantly increased capital costs. Therefore, it is essential to select the most cost-effective design, which meets both process design and mechanical requirements.

The vacuum transfer line is a large, elevated line that routes the vacuum unit feed from the charge heater outlet to the vacuum tower flash zone. Depending on capacity, the line’s diameter can range from 48–84 inches inside diameter and its length is typically 40–70 ft. A typical piping layout for a transfer line includes either individual heater pass outlet piping discharges into the main line routed to the vacuum tower, or half the heater passes discharge into a manifold and the two manifolds discharge into the main line. The piping design group should be consulted to establish the preliminary transfer line routing, including approximate lengths and allowance for thermal expansion. Since transfer lines have a low allowable pressure drop, pressure loses due to fittings should be minimised.

The number of parallel heater tube passes is determined by the required cross-sectional area at the heater outlet to accommodate the large volume of two-phase flow. At the heater outlet, there are typically four to eight separate heater tube passes from one or more cells. While cost-effective heater design favours using fewer tube passes, the need to stay below
the critical velocity necessitates an adequate number of tube passes.

A limiting factor in minimising the vacuum transfer line’s size is the bulk HOT. For a state-of-the-art and deep-cut vacuum unit, the maximum recommended oil temperature in a heater is usually 365–415°C to avoid excessive cracking and coking within the heater coils. To reduce cracking and coking, the HOT must be set low enough to ensure the film temperature does not exceed the maximum recommended oil temperature.

The pressure in the vacuum transfer line keeps decreasing from the HOP to the pressure of the column flash zone, which is normally set at 20–30 mmHg absolute for a deep cut. A typical pressure drop in a vacuum transfer line is about 100–150 mmHg to achieve a deep cut point. Considering the low pressure at the flash zone, the pressure drop of the vacuum transfer line is quite significant. Corresponding to this pressure change, the temperature also changes isenthalpically from the HOT to the flash zone temperature, as the feed goes through adiabatic flashes in the transfer line. Depending on the total pressure drop, a temperature difference of 10–20°C can be expected between the heater outlet and the flash zone. As a result, the vapourisation, density of fluid, volumetric flow and the transport properties all change simultaneously along the transfer line. Therefore, a stepwise, equilibrium simulation is necessary to reflect the continuous changes in a vacuum transfer line.

An important consideration in transfer line design is the two-phase critical velocity, which raises concerns about vibration in the line, especially acoustic-induced vibrations. Field measurements of the vacuum transfer line and calculations using theoretical hydraulic models confirm the existence of critical velocity and its influence on the pressure profile inside a vacuum transfer line.

This phenomenon is difficult to predict for the two-phase flow system. Two-phase critical velocity is much lower than the sonic velocity of the gas phase alone. Therefore, many transfer lines, designed to run under sonic velocity, actually operate at critical velocity, especially near the heater outlet and at the column entrance. The potential impacts of critical velocity are not trivial. The vibration of shock waves could result in failure of the vacuum transfer line. Critical velocity can also lead to excessive entrainment of liquid droplets to the wash zone, even with a well-designed column feed device.1

Heater designers attempt to limit the velocity in the heater coil to reduce vibration problems, and often target a velocity limit of 80% of critical velocity within the heater coil itself. With modern deep-cut columns, avoiding critical velocity throughout the vacuum transfer line often becomes impractical. To the designer, the task of calculating two-phase flow hydraulics is much more difficult to accomplish than single-phase flow hydraulics. The critical velocity is much lower than the sonic velocity of the gas phase alone. Therefore, many two-phase flow hydraulics have been conducted extensively by researchers and developers of hydraulic calculation tools. However, no universal model has been widely accepted. Depending on the criteria and the system studied, different users favour one model over others. This article will focus on how two-phase flow hydraulics can be simulated, providing the model is chosen.

Following a comparison of numerous model performances, the Dukler-Taitel model2 with liquid hold-up from the HTFS method3 was selected to calculate two-phase flow hydraulics with the aid of Fluor’s proprietary hydraulic software. The Dukler-Taitel model was derived from dynamic similarity analysis with experimental data, which is dependent on liquid hold-up but independent of flow regime. By assuming constant slip for two-phase flow, the pressure drop through a conduit can be calculated with adequate accuracy when employing a better correlation of liquid hold-up. For details of the method, refer to the original paper. The liquid hold-up, defined in the HTFS 1992 design report, was developed from HTFS graphical correlations by optimising an analytical function against the original graphical curves. The correlation was tested with the HTFS data bank and was claimed to give better results than the previous HTFS correlations.

For compressible fluids, the volumetric flow of gas changes through a pipe as a result of static pressure variations along the line. The acceleration pressure drop is associated with the expansion of the gas phase as pressure is reduced. It becomes significant in two-phase systems with high mass velocity and low pressures, both of which prevail in a vacuum transfer line. Therefore, the acceleration effect cannot be ignored, and this effect is also calculated in Fluor’s proprietary software. Acceleration effects are most pronounced in tees and expanders, as the static pressure changes significantly across these segments.

![Example of an expander in vacuum transfer line](image_url)

**Figure 1** Example of an expander in vacuum transfer line

Hydraulic models for transfer line calculations

The fluid velocity within the vacuum transfer line is normally high — either close to or at critical velocity. It is generally believed that a homogeneous-phase dispersed flow regime is present at design and normal operations, while a separated-phase annular flow regime is observed during turndown cases.

For a better understanding of the flow regime and hydraulics within a vacuum transfer line, a two-phase flow model should be applied. Over the years, many models have been developed to account for different fluid systems and flow regimes for two-phase flow hydraulics.2 Reviews and model evaluations have been conducted extensively by researchers and developers of hydraulic calculation tools. However, no universal model has been widely accepted. Depending on the criteria and the system studied, different users favour one model over others. This article will focus on how two-phase flow hydraulics can be simulated, providing the model is chosen.

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Figure 1 illustrates an example of the expander in a vacuum transfer line, where the fluid is travelling near critical velocity.

According to Bernoulli’s law, both a fluid’s pressure and velocity contribute to the total energy contained in the moving fluid. At high velocity at the expander inlet, the fluid’s velocity head is a significant component in this sum. As the fluid moves across the gradual expander, the amount of energy lost to friction is relatively low. The velocity is significantly reduced and much of the velocity head is converted to static pressure. The net result is that the static pressure rises across the expander. This effect has been documented in two-phase flow across a sharp expansion, and it would be expected to be even more pronounced across the more gradual expansions in pipe fittings.

For a simple check of the vacuum transfer line’s hydraulic model, a designer should review each point where the velocity drops suddenly — commonly expanders and tees where two process streams combine. As the fluid passes through the expander, the static pressure should rise at these points. If the static pressure does not rise at these points, the calculation warrants further scrutiny to confirm if the fluid has hit the critical velocity.

As the fluid moves through the transfer line and the pressure drops, some portion of the liquid vapourises, adding to the gas flow. There is a debate on whether or not the gas-liquid phase is in equilibrium within the transfer line. Some process designers claim that the vacuum transfer line should be modelled by assuming non-equilibrium between vapour and liquid because of the high transfer line velocity, while other designers prefer to assume significant or complete equilibrium throughout the transfer line.

Non-equilibrium models give better predictions of wash rate to provide sufficient wetting of the wash bed. However, for the purposes of transfer line hydraulics, the most conservative assumption is to consider the fluid in equilibrium throughout the transfer line, as this produces the highest amount of vapour, the highest velocity and, thus, the highest pressure drop. Therefore, complete gas-liquid equilibrium is assumed within the transfer line in this instance.

**Stepwise calculation of transfer line hydraulics**

Ideally, an integrated numerical equation should be used to reflect the
differential changes in properties along the vacuum transfer line. However, such a solution is difficult to find for such complex systems. As a compromise, the vacuum transfer line is split into several segments so that the variation in transport properties is insignificant for each segment. Consequently, properties are approximately constant across the segment, and the hydraulic models described above can be applied to each segment. The total pressure drop is simply the sum of all segments.

This method is similar to the use of a numerical integration method, such as the Simpson method, to solve the differential equations. Applying the Dukler-Taitel model to each segment and summarising total hydraulic changes result in an accurate simulation of vacuum transfer line hydraulics. As a rule of thumb, the pressure change of each individual segment should be no more than 10% of the inlet static pressure of that segment. Separate segments are suggested for all pipe fittings (elbows, expanders, inlet device, and so on). Most importantly, expanders should be placed in a segment of their own, as the static pressure is expected to rise significantly through the expander. When the two-phase fluid flows into the flash zone through an inlet device, all of the velocity energy of the fluid is lost to friction, but the static pressure in the pipe at the exit is essentially the same as that in the column flash zone. The exit loss is due to the dissipation of the discharged jet. There is no pressure drop at the exit except for an insignificant pressure loss due to the inlet device (3.0-3.8 mmHg). There have been cases when extra pressure loss was given to the inlet device in calculations of vacuum transfer line hydraulics. This extra pressure drop changes the pressure profile and thus the transfer line’s design, which will be addressed in detail in a case study.

When the vacuum transfer line is associated with vacuum tower design, normally the temperature at the heater outlet and the pressure at the column flash zone are predetermined. A backward calculation is required for transfer line hydraulics, step-by-step, from flash zone to heater outlet to heater outlet to meet the constraints. To catch fluid property changes as the calculation moves from one segment to another, a process simulation is done by either Pro-II or HYSYS software to flash the stream adiabatically over the expected pressure range of the vacuum transfer line. The changes in properties are then tabulated over the full pressure range of the vacuum transfer line. When the hydraulic calculation goes to the next segment, the properties are updated from the simulated property table according to the calculated current inlet static pressure of that segment. The calculation is iterated until the changes of properties for each segment are insignificant compared to the previous iteration; the calculation is then converged.

Another important issue with respect to the vacuum transfer line is the pressure discontinuity that occurs within it when the internal velocity reaches the critical velocity of the fluid. For an ideal gas system, the maximum velocity that can be achieved is limited by the maximum velocity of a pressure wave travelling in the pipe, which is equivalent to the sonic velocity of the gas. As the gas flows through the vacuum transfer line, its pressure decreases and its velocity increases.

If the pressure drop through the pipe is sufficiently large, the gas velocity exiting the pipe reaches sonic velocity. If the pipe outlet pressure is further decreased or the pipe inlet pressure is further increased, the excess pressure drop occurs beyond the pipe exit. This pressure drop is dissipated in the shock waves and turbulence of the exiting gas. When the ideal gas reaches its sonic velocity, it has reached the maximum mass flow rate that the gas can achieve.

For non-ideal gases and two-phase systems, the maximum mass flow through a piece of pipe is the critical flow. An intuitive way of estimating critical velocity for real gases is to use the method developed for an ideal gas, but with non-ideal gas properties and it usually works well. However, two-phase gas liquid mixtures reach critical flow at a velocity much less than sonic velocity. This phenomenon is better depicted by the separated-phase model. Hewitt and Semeria proposed a separated-phase model to derive the critical velocity of two-phase flow \( V_{CM} \) from the critical velocity of gas: \( \text{Eq. (1)} \)

\[
V_{CM} = \frac{V_{CG} \sqrt{x + (1-x)C}}{\sqrt{x + (1-x)D^2 C^2}}
\]

where \( x \) is the vapour weight fraction, \( C \) is the ratio of gas density to liquid density, \( D \) is the ratio of critical velocity in liquid and gas, and \( V_{CG} \) is the critical velocity of gas.

The critical velocity of gas can be expressed as (Perry’s Handbook):

\[
V_{CG} = \sqrt{\frac{\rho}{\rho_v}} \left( \frac{\bar{M}_w}{M_w} \right)
\]

where \( \rho \) is the density of gas; \( p \) and \( v \) are the pressure and specific volume of gas.

Assuming ideal gas behaviour, Equation 2 can be simplified as:

\[
V_{CG} = \sqrt{\frac{k RT}{M_w}}
\]

where \( k = C_p/C_v \), the ratio of specific heats and \( M_w = \text{mol wt of gas} \).
In this study, we compared the previous correlations with the homogeneous model developed by Buthod and the theoretical approach derived by Kohoutek et al. We found that the calculated critical velocities from these three methods are comparable and consistent. Therefore, the method of Hewitt and Semeria is proposed here because of its simplicity.

**Stepwise method vs conventional method**

Critical flow is a concern in the design or rating of vacuum unit fired heaters, transfer lines and relief header systems. Incorporated within Fluor’s proprietary hydraulic software, an automation program has been developed that updates the transport properties in hydraulic models from the stream properties simulated by Pro-II or HYSYS. With the aid of these programs, a case was studied for a typical vacuum transfer line used in modern vacuum distillation units. A sketch of the vacuum transfer line’s layout, with a branch line connecting the mega-line to one of the heater passes at the heater outlet, is shown in Figure 2. The case presented, not specific to any plant, demonstrates the methodology and procedures used by designers to address key technical issues.

Hydraulic calculations are conducted from the column flash zone, segment by segment, marked by letters all the way to the heater outlet. The simulated hydraulic profile of the vacuum transfer line is illustrated in Figure 3, with location points referring to the layout presented in Figure 2. The calculated results match the specified process constraints: the operating pressure in the flash zone and the heater outlet temperature. Transport properties and the vapourisation of fluids within the vacuum transfer line are simulated by Pro-II using the Improved-Grayson-Streed (IGS) thermodynamic package.

The study of Laird et al. showed that the thermodynamic packages have substantial effects on predictions of vapourisation at the flash zone condition of a vacuum tower. The IGS package gives a vapourisation rate between those given by the Grayson-Streed (GS) and BK10 methods and was chosen to simulate the system of interest.

For a vacuum transfer line with total pressure drops of 100–150 mmHg, the simulated vapourisation changes can be as high as 15 wt% along the vacuum transfer line. Using the automated stepwise approach of this work, the property changes are captured and updated for each segment based on the online calculated static pressure of that segment. The calculated pressure drop of each segment is less than 10% of the inlet static pressure of that segment, which justifies the assumption that properties are constant throughout each individual segment. For comparison, the hydraulic profile calculated by the conventional method (used by many transfer line and heater designers) is also shown in Figure 3. With the conventional calculation, an extra pressure drop (45 mmHg) is assigned to the inlet device as an allowance. Contrasted to the large pressure drop of the inlet device taken by the conventional method, a small and reasonable pressure drop (3.8

![Figure 3 Hydraulic profile of a simulated vacuum transfer line](image3)

![Figure 4 Calculated stream velocity vs critical velocity through a vacuum transfer line](image4)
mmHg) is used in this work, which is consistent with the values reported by Laird et al.¹

As Figure 3 indicates, the simulated total pressure drop of this work is consistent with the results of the conventional method. However, the hydraulic profile of each segment differs substantially between the two methods. Figure 4 shows the calculated velocities of the fluid mixture compared to the critical velocities along the vacuum transfer line using the proposed stepwise method. The current work clearly indicates pressure discontinuities at five locations where the pressure profile of the conventional method showed no sign of calculated velocity ever reaching critical velocity. How can two calculations come to such different conclusions? The differences in this example are due to several factors, which highlight some of the key challenges of this calculation:

- The inlet device typically has a very low pressure drop. The current work uses 3.8 mmHg in its calculation, which is a reasonable estimate for a modern column inlet device.¹ In the calculation using the conventional method, a much higher pressure drop (45 mmHg) is assigned to the inlet device, which leads to a different pressure profile at the inlet to the column. Consequently, the vacuum transfer line is undersized, resulting in a potential choke flow at the column inlet in operation and significant entrainment inside the column flash zone. In the design of a vacuum transfer line, the pressure drop of the inlet device should be confirmed by the vendor and no extra pressure drop should be assigned

- The acceleration effect across an expander is not taken into account in the conventional calculation. Figure 3 shows a monotonic decrease in pressure throughout the transfer line for the conventional calculation, while the stepwise calculation correctly shows a pressure rise across the expanders

- The pressure drop calculated across pipe and fittings differs. The conventional calculation shows a near-constant velocity across each segment, as the calculated pressure drops slightly at each segment except for the inlet device. The stepwise calculation method reveals the actual pressure changes of each segment and demonstrates the correct response of fluid velocity. The effect of pressure change on velocity is clearly shown at location points C, E, H and L in Figure 4 as the fluid passes through the expanders. As the pressure rises across an expander, a corresponding decrease in velocity is predicted using the stepwise modelling approach.

Theoretically, a vacuum transfer line should be designed to remain under critical velocity. However, as a result of uncertainty in calculating the critical velocity and the complexity of two-phase flow hydraulics, it is not unusual to see a vacuum transfer line running at critical velocity — typically at the inlet to the column and near the heater outlet. A deployment of the stepwise simulation method is crucial for providing an accurate hydraulic profile to support design, risk analysis and review.

Conclusion

A stepwise hydraulic calculation has been presented that determines the pressure profile of a vacuum transfer line by linking the hydraulic model to process simulation results. The velocity profile along the transfer line is also reported in relation to the critical velocity of the fluid, which clearly identifies the choke points along the line where the critical velocity is reached. The method offers a more accurate way to specify the pressure profile and line sizing of any two-phase flow system and provides a useful tool for engineering design of the vacuum transfer line. Correct vacuum transfer line design has been shown to enhance profitability, operability and safety of vacuum distillation process units.

References


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