Packing pressure drop prediction at low operating pressure: Is there anything new?

By

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Summary:
At very low operating pressures, the gas Reynolds number is low and distillation columns might be operated in the laminar or transition regime. In such cases, the friction factor cannot be seen as constant but becomes a function of the gas Reynolds number. This dependency is confirmed by experimentally evaluated friction factors for gauze packing in the laminar and turbulent regime and from such data the critical Reynolds number can be deduced.

Rating programs which do not correctly reflect the friction factor will predict a far too low pressure drop in the laminar regime.

Introduction

Prediction of pressure drop in counter-current operated packing columns is well established for a wide range of physical properties and loads. Generalized pressure drop correlations and published correlations based on packing geometry allow in many cases to predict the pressure drop with an accuracy of 20%. Particularly, correlations adjusted to specific packing types, as typically included in the hydraulic software of packing vendors or organisations such as Fractionation Research, Inc. (FRI) or Separations Research Program (SRP), are expected to predict pressure drop more accurately.

The required accuracy of predicted pressure drop values depends strongly on the operating conditions: in applications with high operating pressures, the specific pressure drop itself might not be of particular importance; more important is a correctly predicted maximum capacity. The opposite holds true for columns operated at low operating pressure: the bottom pressure needs to be accurately predicted since this will influence the bottom boiling temperature. When the bottom pressure is higher than predicted, thermal decomposition might occur, or the concentration of the light key cannot be achieved, resulting in either an off-spec product or loss in yield. Although columns are usually not operated close to the maximum capacity for such applications, the packing pressure drop is of major importance.

Hydraulic loads in terms of F-factor (gas load factor) and liquid load are low to moderate in deep vacuum distillations and the physical properties (liquid to gas density ratio, surface tension and viscosities) are not considered to be close to critical. Therefore, it should be expected that pressure drop predictions are accurate.

Pressure Drop Below Loading Point

The domain of structured packing is vacuum distillation due to its low pressure drop per theoretical stage. Figure 1 indicates the calculated pressure drop for MellapakPlus^{TM} 252.Y, the most commonly used high performance structured packing in industry. The values are based on Sulcol^{TM} V3.0.8, a freely available hydraulic rating program supplied by the packing manufacturer, Sulzer Chemtech. All three pressure drop curves, which indicate the pressure drop per meter of packing height as a function of the F-factor, are based on the same assumed liquid physical properties; only the specific liquid loads are different, i.e. $l_{spec}=0.5,\ 1.0$ and $2.0\ m^3/(m^2h)$. The curves indicate that up to an F-factor of $F_v=4\ Pa^{0.5}$ the liquid phase has no relevant impact on the resulting specific pressure drop for these relatively low liquid loads.

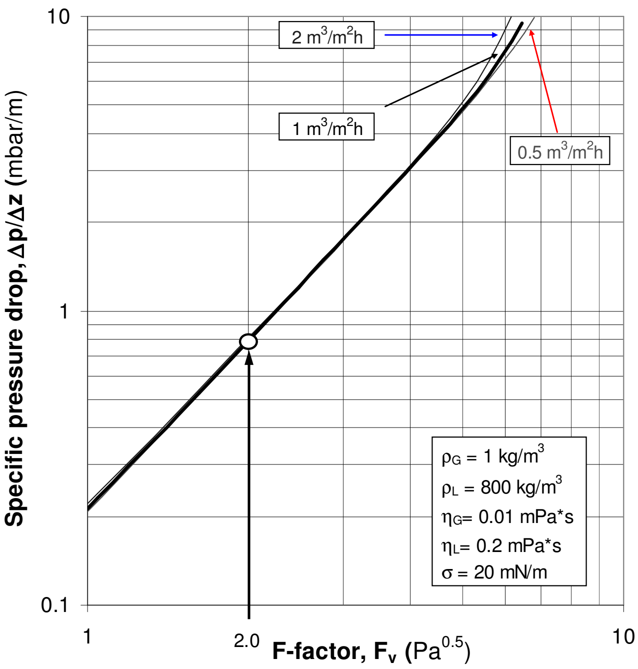

Figure 1: Specific pressure drop of Mellapak 252.Y for varying F-factor and for 3 specific liquid loads based on Sulcol^{TM} V3.0.8

At higher F-factors, the pressure drop is increasing with increased liquid flow rates and thus the maximum capacity is affected.

Figure 1 indicates this outcome and can be easily explained by the liquid holdup, which is small at low specific liquid loads and will thus affect the pressure drop only marginally as long as the gas load factor remains far from the maximum capacity or flooding point.

In deep vacuum distillation, when minimization of pressure drop is the key, the columns are designed in most cases to be operated at moderate gas load factors in order to reduce the overall pressure drop and the resulting liquid loads are typically low. In this operating region, the impact of the liquid load and the liquid physical properties are minor: only the frictional pressure drop of the gas phase is causing the pressure drop as long as the F-factor is below the loading point. This outcome is of importance, when the impact of the friction factor is to be investigated.

From pressure drop measurements in pipes the following relation is well known [1]:

$$\frac{\Delta p}{\Delta z} = \frac{4 \cdot f}{d} \cdot \frac{\rho \cdot u^2}{2} \qquad (1)$$

The pressure drop per unit length is proportional to the density times velocity squared, $\rho \cdot u^2$, and is inversely proportional to the pipe diameter, d. The fanning friction factor, f, is a function of the Reynolds number. For Reynolds numbers below 2300, the flow regime is laminar and the fanning friction factor is $f = 16/Re$. For Reynolds numbers above 2300, the fanning friction factor is a function of the Reynolds number <u>and</u> the pipe roughness. For hydraulic smooth pipes, the fanning friction factor does not approach a constant value and becomes smaller with increasing Reynolds number. Only in the fully developed turbulent flow regime, the friction factor approaches a constant value.

A similar approach was chosen by Zogg [2] to characterize the pressure drop in Sulzer wire gauze structured packing in 1972. He used a test cell which consisted of two packing layers and he measured the pressure drop depending on the gas throughput. The friction factor, or drag coefficient, was then calculated based on the experimentally determined pressure drop values using the following approach:

$$\frac{\Delta p}{\Delta z} = \frac{c_f}{d_h} \cdot \frac{\rho_G \cdot u_{G,s}{}^2}{2} \quad \rightarrow \quad c_f = 2 \cdot \frac{\Delta p}{\Delta z} \frac{d_h}{\rho_G \cdot u_{G,s}{}^2} \tag{2}$$

Where c_f is the drag coefficient and d_h the hydraulic diameter of the packing. He used the following definitions for the hydraulic diameter and the gas Reynolds number:

$$d_h = \frac{4}{a} \tag{3}$$

$$Re_G = \frac{u_{G,s} \cdot \rho_G \cdot d_h}{\eta_G} \tag{4}$$

Zogg used the superficial velocity to determine the Reynolds number and evaluated the data accordingly. Figure 2 below is a reprint from his PhD thesis from the ETH in Zürich, Switzerland (page 41) and the circles were added to indicate where the flow regime changes from laminar to turbulent.

Figure 2 shows three groups of curves, namely for corrugation angles of φ = 60°, 45° and 30°. The corrugation angle is measured with respect to the vertical. Packing types with an angle of 45° are known as Y-types whereas X-types have commonly a 30° angle. Structured packing with a corrugation angle of 60° has not been marketed. Zogg used different test cell widths, B, for his model to measure pressure drop and the ratio B / d_h is used as parameter.

The interpretation of the experimental results is:

- The friction factor is relatively strongly dependent on the corrugation angle
- The friction factor is a function of the Reynolds number
- The critical Reynolds number for a corrugation angle of φ = 45° is $Re_{crit\_Y} \approx 250$ and for φ = 30° it is $Re_{crit\_Y} \approx 450$ for column diameters > $100 \cdot B/dh$
- The friction factor is depending on the ratio of B/d_h, which reflects the impact of the column diameter on pressure drop

This outcome is in agreement with fundamental findings in fluid dynamics and it should be expected that any hydraulic rating tool for packing will include such behaviour, at least qualitatively.

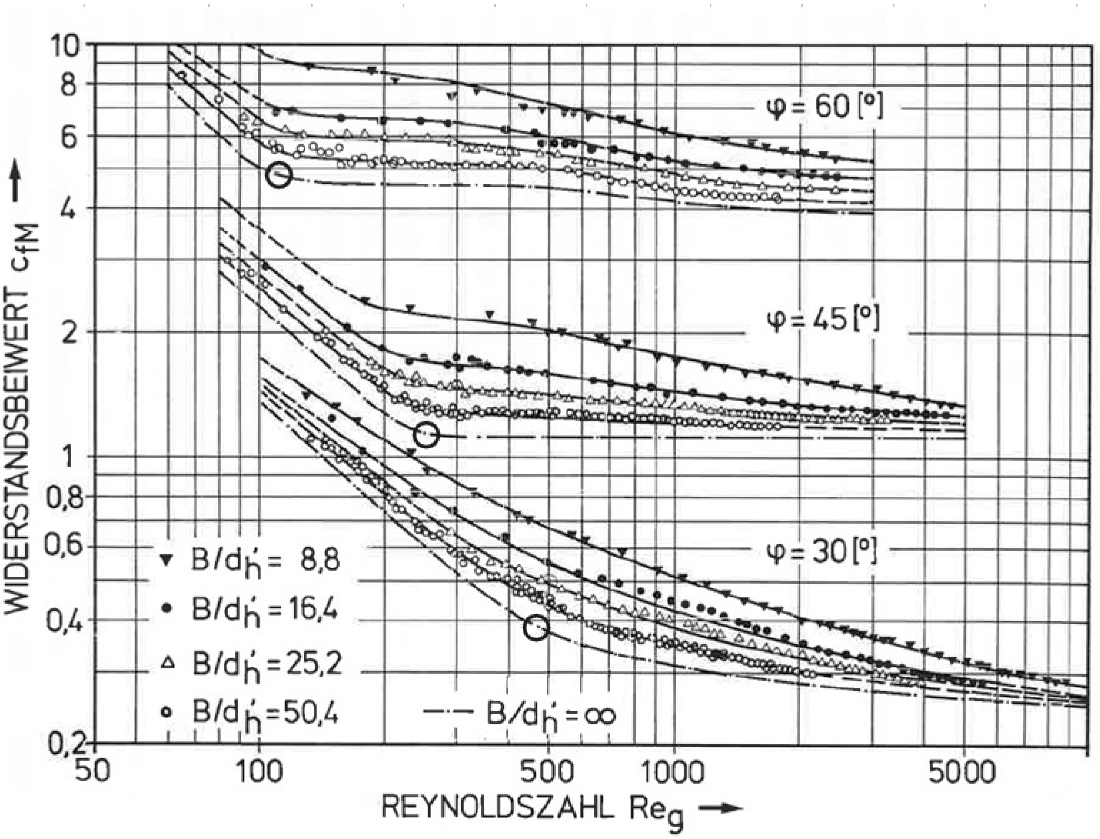

Figure 2: Friction factors for Sulzer wire gauze packing with a specific area of 500 m^2/m^3 and different corrugation angles, φ . Graph taken from [2]

Predicted Pressure Drop by Hydraulic Rating Software

Six (6) hydraulic rating software tools were compared, applying the same hydraulic loads and physical properties. Five of the tested rating tools were from packing vendors. The purpose of the comparison was to evaluate how hydraulic rating programs quantify the friction factor. Since the friction factor is markedly changing with low Reynolds numbers, industrial applications operated in the laminar regime are of particular interest of the investigation. Deep vacuum applications result in low gas Reynolds numbers, which might not be intuitively expected since the gas velocities are very high in these applications.

Packing types having a low pressure drop per theoretical stage are favourably used in such columns and MellapakPlus 252.Y and Sulzer BXPlus™ can be considered the benchmark for metal sheet and wire gauze packing, respectively.

In order to compare the hydraulic results of various software programs, the following conditions were assumed: liquid and vapour physical properties, liquid load ($l_{spec}=2\ m^3/m^2h$) and F-factor ($F_v=2.0\ Pa^{0.5}$) were assumed constant. The gas density was varied and thus the gas throughput was adjusted to keep the F-factor constant. In addition, the column diameter was chosen to be larger than 1 m in order to exclude wall effects on pressure drop. Figure 3 indicates the resulting gas Reynolds numbers for the two packing types used as benchmark with the assumed physical properties and for the investigated range in gas density.

Table 1 below shows the calculated specific pressure drop values for MellapakPlus 252.Y and for Sulzer BXPlus packing, using Sulcol. Results obtained by FRI's Device Rating Program, DRP™, are listed for MellapakPlus 252.Y; no data are reported for Sulzer BXPlus since it is not included in this rating program. In addition, the outcome of a rating program of a packing vendor which offers high performance structured packings with similar specific areas as the benchmark packing is also listed in table 1 and is referred to as Vendor X. All results were based on the latest software version available at the time of the investigation (March 2013).

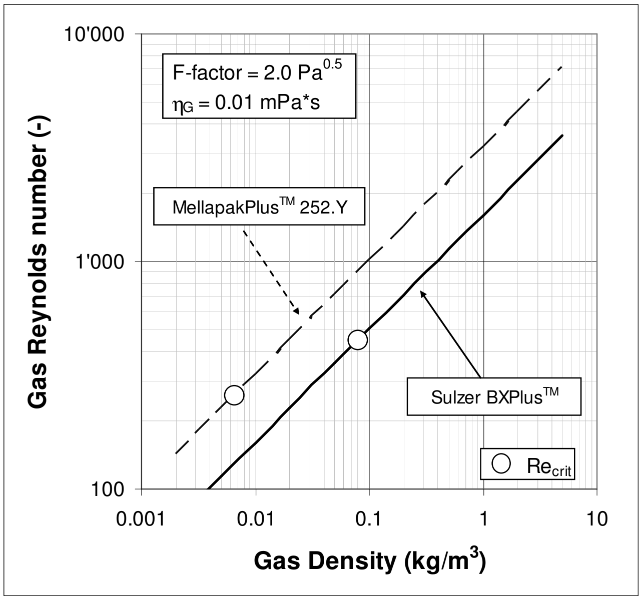

Figure 3: Gas Reynolds numbers at $F_v = 2.0\ Pa^{0.5}$ as function of gas density for MellapakPlus 252.Y (d_h=0.016 m) and Sulzer BXPlus (d_h=0.008 m)

Table 1: Calculated pressure drop for 2 types of structured packing:
a) Metal sheet with a specific area of approx. 250 m^2/m^3 ; corrugation angle $\varphi = 45°$
b) Wire gauze packing with a specific area of approx. 500 m^2/m^3 ; corrugation angle $\varphi = 30°$

Column ID > 1 m			**a) Metal sheet packing**			**b) Wire gauze packing**		
ρ_L = 800 kg/m^3			**a_{Geo} ≈ 250 m^2/m^3 - corr. angle: 45° (Y-type)**			**a_{Geo} ≈ 500 m^2/m^3 - corr. angle: 30° (X-type)**		
η_L= 0.2 cP	**η_G= 0.01 cP**		Sulcol™	DRP™	Vendor X	Sulcol™	DRP™	Vendor X
σ = 20 mN/m			V 3.0.8	V 2.2	Vers. March 13	V 3.0.8	V 2.2	Vers. March 13
I_{spec} = 2 m^3/m^{2}h			M252.Y	M252.Y	similar M252.Y	BXPlus	BXPlus	similar area
ρ_G (kg/m^3)	**u_G** (m/s)	**F_v** (Pa$^{0.5}$)	**Δp/Δz** (mbar/m)	**Δp/Δz** (mbar/m)	**Δp/Δz** (mbar/m)	**Δp/Δz** (mbar/m)	**Δp/Δz** (mbar/m)	**Δp/Δz** (mbar/m)
0.002	**44.7**	**2.00**	**1.68**	**0.82** [1]	**0.95**	**3.84**	**n/a**	**0.76**
0.005	**28.3**	**2.00**	**1.34**	**0.82** [1]	**0.95**	**2.66**	**n/a**	**0.76**
0.01	**20.0**	**2.00**	**1.17**	**0.82** [1]	**0.95**	**2.05**	**n/a**	**0.76**
0.02	**14.1**	**2.00**	**1.05**	**0.82** [1]	**0.95**	**1.63**	**n/a**	**0.76**
0.05	*8.9*	*2.00*	*0.94*	*0.82* [1]	*0.95*	*1.25*	*n/a*	*0.76*
0.1	*6.3*	*2.00*	*0.89*	*0.82* [1]	*0.95*	*1.07*	*n/a*	*0.76*
0.2	*4.5*	*2.00*	*0.85*	*0.82* [1]	*0.95*	*0.93*	*n/a*	*0.76*
0.5	*2.8*	*2.00*	*0.82*	*0.82* [1]	*0.95*	*0.82*	*n/a*	*0.76*
1	*2.0*	*2.00*	*0.81*	*0.82* [1]	*0.95*	*0.76*	*n/a*	*0.76*
2	*1.4*	*2.00*	*0.81*	*0.87*	*0.95*	*0.72*	*n/a*	*0.76*
5	*0.9*	*2.00*	*0.80*	*1.18*	*0.95*	*0.68*	*n/a*	*0.76*

[1] Warning by DRP: calculated vapour Reynolds number set to minimum value of 5000 for structured packing

The results from table 1 reveal that only Sulcol shows a dependency of the pressure drop on the gas density: the values increase with decreasing gas density. However, the impact of the gas density on the pressure drop is significantly more severe for the X-type packing with a specific area close to 500 m^2/m^3. Sulcol, DRP and the software tool from Vendor X achieve comparable results at gas densities higher than 0.5 kg/m^3 whereas the predicted pressure drop deviates up to a factor of 2 for Y-type metal sheet and more than a factor of 3 for wire gauze X-type packing at gas densities below 0.005 kg/m^3.

Interpretation of the Results

In order to interpret the outcome of the values in table 1, equation 2 is preferably written using the F-factor instead of $\rho_G \cdot (u_{G,s})^2$:

$$F_V = u_{G,s} \cdot \sqrt{\rho_G} \tag{5}$$

$$\frac{\Delta p}{\Delta z} = \frac{c_f}{d_h} \cdot \frac{F_v^2}{2} \tag{6}$$

From equation (6) it can be interpreted that the pressure drop is expected to be constant with a constant F-factor if the friction factor remains unchanged and for a fixed hydraulic diameter and corrugation angle. The friction factor can only be expected to be constant when the resulting gas Reynolds number is higher than the critical gas Reynolds numbers.

Table 2 lists the Reynolds numbers and the ratio of Reynolds to critical Reynolds number. The friction factor shown in table 2 can be readily obtained by applying equation (2) to the results from table 1. It is obvious, that when the pressure drop remains constant with the assumed conditions and with variable gas density, that the friction factor also remains constant. Therefore, only the friction factors retrieved from Sulcol are listed in table 2. The outcome of the other rating tools was:

DRP:	c_f = 0.65 for M252.Y
Vendor X:	c_f = 0.75 (metal sheet) and c_f = 0.3 (wire gauze)

From table 2 it can be seen that the critical Reynolds number is already closely approached with a gas density of 0.1 kg/m^3 for Sulzer BXPlus at an F-factor of 2.0 $Pa^{0.5}$. A gas density of 0.1 kg/m^3 might already be achieved at operating pressures of 20 mbar, which is not considered to be an extremely low operating pressure. MellapakPlus 252.Y has a significantly increased pressure drop at very low gas densities corresponding to operating pressures below 3 mbar.

Table 2: Reynolds numbers and friction factors
a) Metal sheet with a specific area of approx. 250 m^2/m^3 ; corrugation angle $\varphi = 45°$
b) Wire gauze packing with a specific area of approx. 500 m^2/m^3 ; corrugation angle $\varphi = 30°$

Column ID > 1 m
ρ_L = 800 kg/m^3
η_L= 0.2 cP **η_G= 0.01 cP**
σ = 20 mN/m
l_{spec} = 2 m^3/m^{2}h

			a) Metal sheet packing			**b) Wire gauze packing**		
			a_{Geo} ≈ 250 m^2/m^3 - corr. angle: 45° (Y-type)			**a_{Geo} ≈ 500 m^2/m^3 - corr. angle: 30° (X-type)**		
			d_h = 0.016 m $Re_{G,crit}$ =250		Sulcol™ V 3.0.8 M252.Y	d_h = 0.008 m $Re_{G,crit}$ =450		Sulcol™ V 3.0.8 BXPlus
ρ_G (kg/m^3)	**u_G** (m/s)	**F_v** (Pa$^{0.5}$)	Re_G [-]	$Re_G/Re_{G,crit}$ [-]	**c_f** [-]	Re_G [-]	$Re_G/Re_{G,crit}$ [-]	**c_f** [-]
0.002	**44.7**	**2.00**	**143**	**0.57**	**1.34**	**71**	**0.16**	**1.54**
0.005	**28.3**	**2.00**	**226**	**0.91**	**1.06**	**113**	**0.26**	**1.06**
0.01	**20.0**	**2.00**	**320**	**1.3**	**0.9**	**160**	**0.36**	**0.82**
0.02	**14.1**	**2.00**	*453*	*1.8*	*0.83*	**226**	**0.51**	**0.65**
0.05	**8.9**	**2.00**	*714*	*2.9*	*0.75*	**357**	**0.81**	**0.50**
0.1	**6.3**	**2.00**	*1011*	*4.0*	*0.71*	**505**	**1.1**	**0.43**
0.2	*4.5*	*2.00*	*1429*	*5.7*	*0.67*	*714*	*1.6*	*0.37*
0.5	*2.8*	*2.00*	*2264*	*9.1*	*0.65*	*1132*	*2.6*	*0.33*
1	*2.0*	*2.00*	*3197*	*13*	*0.64*	*1599*	*4*	*0.30*
2	*1.4*	*2.00*	*4527*	*18*	*0.63*	*2264*	*5*	*0.29*
5	*0.9*	*2.00*	*7144*	*29*	*0.63*	*3572*	*8*	*0.27*

When comparing the calculated friction factors in table 2 with the experimentally retrieved data by Zogg in figure 2, then these values are in good agreement for the wire gauze packing Sulzer BXPlus. For the metal sheet packing MellapakPlus 252.Y, the agreement is good in the laminar regime but the friction factors are predicted significantly lower by Sulcol in the turbulent region. This can be explained by the fact that the roughness of the metal sheet is smoother than of wire gauze packing and therefore the friction factor is lower in the turbulent regime. The roughness of the surface is expected to have no impact in the laminar regime and confirms the outcome from Sulcol for MellapakPlus 252.Y

Industrial Vacuum Applications

The conclusion from above tables was that for Sulzer BXPlus the friction factors must not be considered constant when the gas Reynolds number is close to or lower than 450. Such conditions are indeed relevant in the chemical and petrochemical industry and figure 4 shows important vacuum applications and typical design conditions thereof, i.e. design F-factor and gas density. The top operating pressure will depend on the process licensor and therefore, the indicated data points in figure 4 can vary for the indicated applications. The curves are calculated for Sulzer BXPlus packing, a gas viscosity of 0.01 cP and indicated constant gas Reynolds numbers.

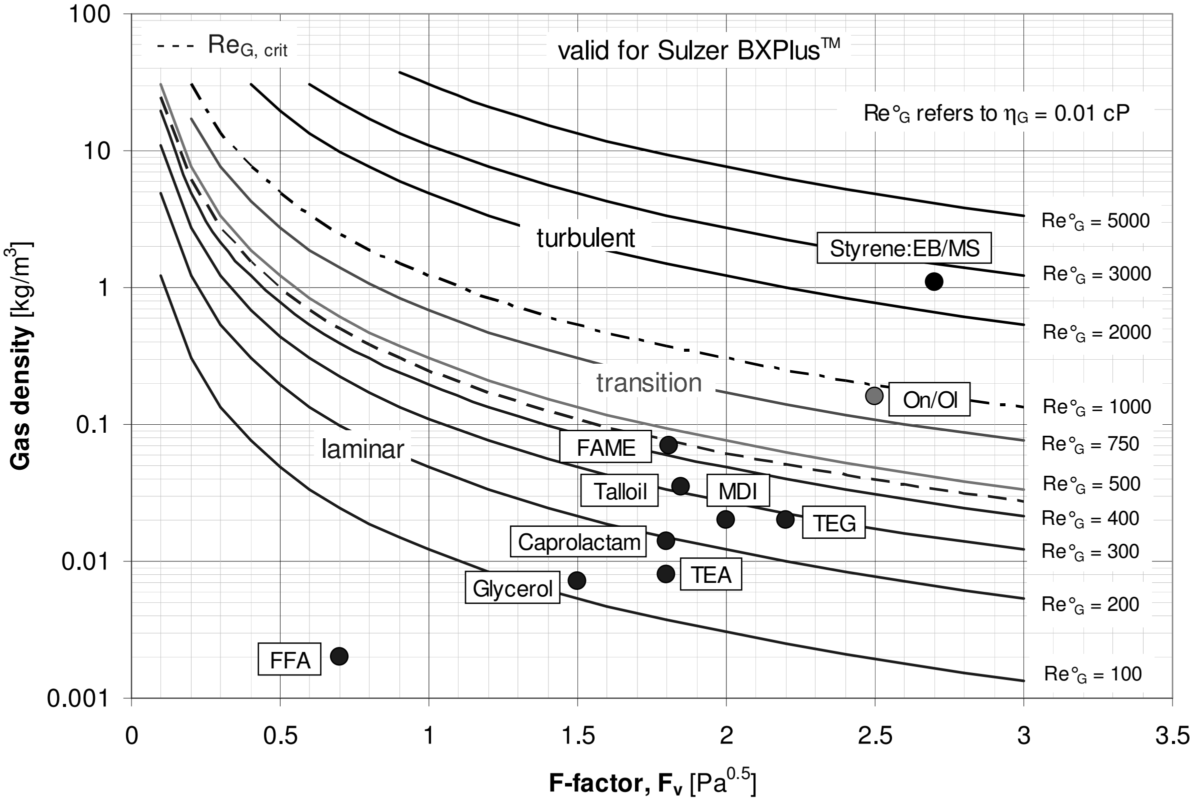

Figure 4: Typical design conditions for industrially relevant applications which are designed at low operating pressure. The following abbreviations are used:
FAME = fatty acid methyl ester ; FFA = free fatty acid stripper ; MDI = methylene diisocyanate
TEA = triethanol amine ; TEG = triethylene glycol ; On/Ol = cyclohexanone / cylcohexanol

Conclusions / Recommendations

Various hydraulic rating programs were tested with the aim to investigate the use of friction factors in vacuum applications. The astonishing outcome was that four (4) of the tested rating tools did not include a gas Reynolds number dependent friction factor. Beside Sulcol, only one rating program from a European packing vendor included variable friction factors, however using a weaker dependency on the gas Reynolds number than experimentally measured.
Inappropriate calculation of the friction factor can lead to drastic under-prediction of pressure drop in deep vacuum applications.

Measurements to quantify the impact of the gas Reynolds number on the friction factor were published in 1972 by Zogg and several papers have been published since, addressing this issue: in 1986 Bravo et al. [3] proposed a simple method to account for the friction factor and in 1989 Stichelmayer et al. [4] proposed a modification to Bravo's approach. Many other authors have addressed the topic, too, but obviously, the information has not found its way into all hydraulic rating programs.

The user of any hydraulic rating software should make sure that his tool is handling friction factors correctly when used to design low pressure distillation columns. When the design gas density is below 0.1 kg/m^3, the following procedure is recommended for testing:

1. Qualitative check:
    a. Perform the hydraulic calculation as per the required design conditions and determine the specific pressure drop.
    b. Decrease the gas density by a factor of 100 and decrease the mass flow rate of the gas/vapour by a factor of 10: this will result in the same F-factor. Keep all other properties the same. Determine the pressure drop with these conditions.
    c. Compare the two results: it is expected that the pressure drop has increased. Should the results be the same, then your tool might very likely not consider friction factors appropriately and you must not use it in the laminar regime.

2. Quantitative check
    a. Perform the hydraulic calculation as per the required design conditions and determine the specific pressure drop.
    b. Determine the superficial gas velocity resulting from your design:
    $$u_{G,s} = F_v / (\rho_G)^{0.5}$$
    c. Determine the hydraulic diameter of the structured packing used, as per equation (3): $d_h = 4 / a$ and determine the corrugation angle, φ.
    d. Based on the calculated specific pressure drop (in units of Pa/m), the hydraulic diameter (m), the gas velocity (m/s) and gas density (kg/m^3) the friction factor can be determined by applying equation (2)
    e. Determine the gas Reynolds number as per equation (4)
    f. Compare the retrieved friction factor at the calculated gas Reynolds number with the curves given in figure 2. Make sure you use the curve with the correct corrugation angle.

The proposed methods will allow the design engineer to easily check the capability of the hydraulic rating tool for pressure drop critical applications.

Symbols

a	(m^2/m^3)	Specific packing area
B	(m)	Width of model used by Zogg
c_f	(-)	Friction factor or drag coefficient for packing
d	(m)	Pipe diameter
d_h	(m)	Hydraulic diameter of packing
f	(-)	Fanning friction factor for pipe
F_v	$(Pa^{0.5})$	F-factor, gas load factor $F_v=u_{G,s}\cdot\rho_G^{0.5}$
l_{spec}	(m^3/m^2h)	Specific liquid load
Re	(-)	Reynolds number $Re= u\cdot\rho\cdot d_h/\eta$
u	(m/s)	Velocity
Δp	(Pa)	Pressure drop, pressure difference
$\Delta p/\Delta z$	(Pa/m)	Specific pressure drop

Greek

σ	(N/m)	Surface tension
η	$(Pa\cdot s)$	Viscosity
φ	(°)	Angle of corrugation channel from the vertical
ρ	(kg/m^3)	Density

Indices

V or G	Vapour or Gas
L	Liquid
s	Superficial

Remark: the above units need to be applied in the equations of this paper. The tables and figures in the paper may indicate other units.

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