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Gas Cleaning: An analysis on Rapsody

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Abstract

The operationalization of gas cleaning devices *CKB Kunststoffen*, which make use of the principle of countercurrent liquid/gas flows, is mostly dependent of the decision-making tool Rapsody. The choice of packing material used in the washing tank will be fully determined by Rapsody. A case study of a washing tank of *CKB Kunststoffen* will be analyzed and advice will be given on the type of packing material and other choices made in the construction of the washing tank. Furthermore, Rapsody will be validated by investigating and comparing the different models used in their calculation methods.

1 Introduction

Many farms in the bio industry release polluted gasses as a result of their labor. Ideally, these gasses would be no problem for communities living near these farms, but unfortunately, more and more complaints come from those communities about bad smells and slightly toxic gasses. Moreover, the European Union is setting regulations and policies about a clean environment in agriculture. Therefore, these gasses must be captured and cleaned before being released, because otherwise farms are not allowed to continue in bio industry. Also in industry, for example in galvanic processes, toxic fumes emerge that need cleaning before the rest is released into the atmosphere.

1.1 Model of a gas cleaning device and Rapsody

CKB Kunststoffen is a company that provides the construction of a variety of systems, like complete Galvano systems, storage tanks, extraction systems, process installations, filter systems, plastic piping systems and much more. One particularly interesting project of *CKB* is the construction of a gas cleaning device which addresses problems as mentioned above. This device cleans the polluted gasses with help of hydraulic diffusion processes.

Essentially, the gas cleaning device is an enormous tank in which the polluted gasses will be cleaned. Clean water is pumped to the top side of the tank, and polluted gasses are coming from the bottom of the tank. Inside the tank, a huge number of small, porous packing materials are stored. When the liquid is moving through these materials, they ensure that the surface of the liquid interacts as much as possible with the polluted gasses, in order for the polluted gasses to be captured in the liquid particles. The polluted liquid will then be disposed to some place where people will not be bothered by them. In the end, the gasses, who are now clean, will leave the tank at the top side. A representation of this process can be found in Figure 1.

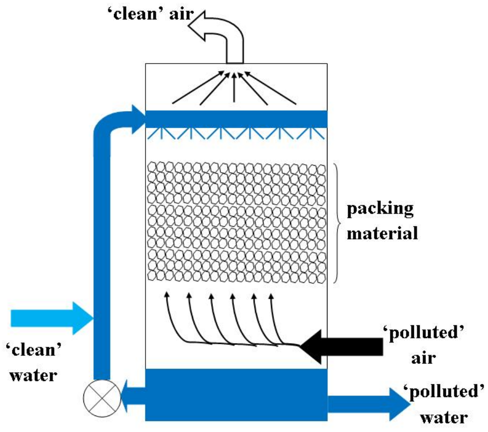

FIGURE 1: Schematic representation of the gas-cleaning process – clean water and polluted gases are brought into contact in a volume filed with 'packing material', leading ideally to cleaned gases and polluted water that can be treated afterwards.

For the modelling and construction of this device, *CKB* uses a mathematical tool called Rapsody to determine (amongst other things) what kind of packing material to use, what the dimensions of the device should be, and to make sure the washing tank can be operational. From *CKB*, the question arose how reliable the Rapsody tool is in its mathematical context.

2 Theoretical framework of packed columns in countercurrent flow

The diffusion process of the polluted gasses and the clean water are complex (taking into account the packing material used in the device), and therefore the tool Rapsody is used to carry out these difficult calculations regarding the hydraulic processes. Still, a lot of aspects should be taken care of. In 'Distillation: Equipment and Processes', specifically the chapter 'Packed Columns' written by Máckowiak [1], most of the modelling in countercurrent flow is explained. When Máckowiak speaks of 'randomly packed columns', he is talking about a gas cleaning device like *CKB Kunststoffen* is producing. He defines this as the following: 'Packed columns are mainly operated in countercurrent gas/liquid flow of both phases, in which the liquid, driven by gravity, flows down the mass transfer zone consisting of the random or structured packing in the form of a trickle film or falling droplets. The gas or vapor as the continuous phase flows upwards from the bottom to the top of the column'.

The one thing to be concerned about in engineering packed columns, is to make sure the column does not flood. When the operating point of a packed column is flooding, this means that the liquid is residing in the column longer than the column can hold. This can have a lot of causes, for example because of the high gas flow going through the column, a high liquid load going through the column, or the type of packing material 'blocking' the liquid and gas flows. The importance of flooding in packed columns is that the washing tank cannot be operational if the tank floods. It is therefore necessary that the washing tank is not flooding at all times. Let us assume that at some point, the column will be flooding. This two-dimensional point can be defined by the capacity of gas and the capacity of liquid in the column. An infinite set of flooding points exists, and these points altogether build the flooding line. When using Rapsody to determine this line, the red line in Figure 2 illustrates this flooding line.

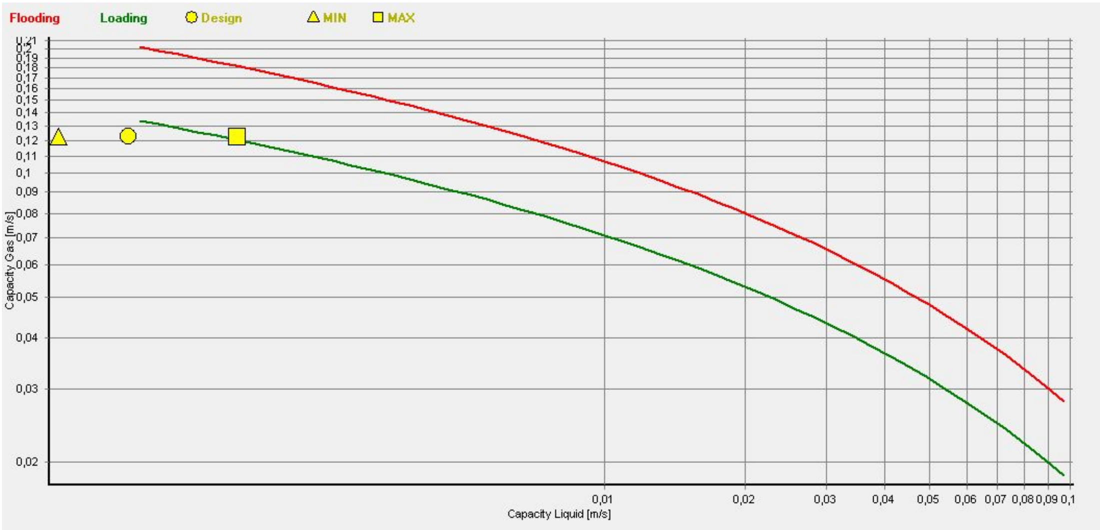

FIGURE 2: The red line represents the flooding line and the green line represents the loading line

Different models are constructed to explain the flooding points and the flooding lines, for example by Engel & Stichlmair and by Billet & Schultes which will be discussed later. The loading line, which is the optimal point for operationalization according to Mackowiak, is at 65% of the gas capacity of the flooding line. A representation of the loading line, which is the green line, can also be seen in Figure 2. In most cases it is optimal to operate near this loading line. However, it can sometimes be beneficial to operate above the loading line, at up to 80% of the gas capacity of the flooding line. The flooding of a column is always because the pressure drop is increasing significantly and the liquid holdup is increasing greatly. Because the flooding and loading lines are highly dependent of the pressure drop and liquid holdup, we will discuss these two aspects.

2.1 Pressure drop

The pressure drop $\frac{\Delta p}{H}$ is defined as the change in pressure (Δp) over the random packing height (H). The pressure drop affects the gas phase flowing through a packed bed. It has huge impact on the total operation costs, making it an important factor when choosing the packing material or fixing other parameters. Furthermore, the pressure drop is connected to the behavior of types of packing material, specifically in which operating range the packing material works. In one-phase flows with dumped packings, a general formula has been derived to calculate the dry pressure drop (it is dry since it is not a countercurrent flow, only one-phase flow):

$$\frac{\Delta p_0}{H} = \psi_0 \cdot (1 - \phi_P) \cdot \frac{1 - \epsilon}{\epsilon^3} \cdot \frac{F_V^2}{d_p \cdot K} \tag{1}$$

In equation 1, ψ_0 is defined as the resistance factor, and ϕ_P is defined as the form factor of the packing material. Both the resistance and form factor are found by using experimental data. Furthermore, F_V is the gas capacity factor, ϵ is the void fraction of the packing material, and d_p is the particle diameter defined as

$$d_p = 6 \cdot \frac{(1-\epsilon)}{a_{geo}},$$

where a_{geo} is the specific surface area (m^2/m^3) of the packing material. Lastly, K accounts for the influence of the wall of the gas tank on the packing material. The dry pressure drop is therefore dependent on the packing material and the gas capacity factor F_V, which is dependent on the gas velocity U_V and the density of the gas ρ_V:

$$F_V = U_V \cdot \sqrt{\rho_V}.$$

To determine the irrigated pressure drop, that is the pressure drop in countercurrent flow, an extension of this formula is used:

$$\frac{\Delta p}{H} = \psi_0 \cdot (1-\phi_P) \cdot \frac{1-\epsilon}{\epsilon^3} \cdot \frac{F_V^2}{d_p \cdot K} \left[1 - \frac{C_B}{\epsilon} \cdot a_{geo}^{\frac{1}{3}} \cdot u_L^{\frac{2}{3}}\right]^{-5}, \tag{2}$$

$$\frac{\Delta p}{H} = \psi_0 \cdot (1-\phi_P) \cdot \frac{1-\epsilon}{\epsilon^3} \cdot \frac{F_V^2}{d_p \cdot K} \left[1 - \frac{C_C}{\epsilon} \cdot a_{geo}^{\frac{2}{3}} \cdot (v_L \cdot u_L)^{\frac{1}{3}}\right]^{-5}. \tag{3}$$

The extended formulas in equations 2 and 3 only needs three new parameters compared to the formula for dry pressure drop: the liquid load u_L, the viscosity of the liquid v_L, and a constant C_B (for equation 2) or C_C (for equation3). The constants can be determined by experimental data and are dependent on a certain type of packing material, just like the resistance coefficient. Both are a characteristic of the packing material. The constant C_B must be used when operating with turbulent liquid flow, whereas the constant C_C must be used when dealing with non-turbulent liquid flow and when operating below the loading line. The constant C_C is expected to have the same value for different kinds of packing material when operating below the loading line.

2.2 Liquid holdup

Liquid holdup is defined as the fraction of the column that is occupied by liquid. The importance of the liquid holdup can be found in that it is a parameter that can help predict the irrigated pressure drop and the liquid residence time in packed beds.

Additionally, it has an influence on the construction of the packed column. When encountering turbulent liquid flow, the liquid holdup is dependent on the liquid load u_L and the specific geometrical packing dimensions, as seen in equation 4:

$$h_L = C_P \cdot \left[\frac{u_L^2 \cdot a_{geo}}{g}\right]^{\frac{1}{3}}, C_P = 0.57. \tag{4}$$

In equation 4, g stands for the acceleration due to gravity. However, when the liquid flow is non-turbulent, the viscosity v_L of the liquid flow is also needed for determining the liquid holdup, as seen in equation 5:

$$h_L = \frac{3}{4} \cdot \left[\frac{3}{g}\right]^{\frac{1}{3}} \cdot a_{geo} \cdot (v_L \cdot u_L)^{\frac{1}{3}}. \tag{5}$$

In both cases, the liquid holdup has an accuracy of <20%, which is reasonable to work with when operating close to the loading point. At the flooding point, the liquid holdup will approximately be twice as big as the liquid holdup on the loading point, which is confirmed by tests in Rapsody. Again, there exists a slightly more accurate but complicated way of calculating the liquid load between the loading and flooding line. For these calculations, the relative gas capacity must be known. These calculations can be found in Mackowiak's work [1]

3 Literature review Rapsody

Rapsody is mostly built to ensure that the washing tank (or as the literature calls it, 'the packed column') can be operational. The challenge lies within the restraints of making sure that the washing tank does not flood, but at the same time wanting for the liquids to interact with the polluted gasses as much as possible. It is very important to remember that Rapsody gives absolutely no information on the cleanliness of the gas that leaves the washing tank.

The theory and modelling of Rapsody, like the fluid dynamics and countercurrent-flow, is based on 3 papers. These are:

1. *Fluiddynamik in Füllkörper- und Packungskolonnen für Gas/Flüssigsysteme Chemie* from V. Engel and J. Stichlmair [2].
2. *Prediction of Mass Transfer Colums with dumped and arranged Packings* from R. Billet and M. Schultes [3].
3. *Packed Columns* from A.B. Mersmann and A. Deixler [4].

The article written by Mersmann & Deixler could not be found online. Furthermore, this same article written by Mersmann & Deixler is inherently different in its model compared to the other two models when applying Rapsody. This will become clear when discussing the practical use of Rapsody. However, the usage of the model of Mersmann & Deixler is very limited when using Rapsody, so it may not be a huge problem that this article is not available.

3.1 Model of Billet & Schultes

The model of Billet & Schultes [3] can be divided into four parts. In these four parts, they give universal equations and formulas about an essential part of mass transfer columns and dumped or arranged packings in a countercurrent flow. The first part is the calculation of the mass transfer efficiency. In the second part, calculations for the pressure drop are given. Subsequently, the third part is about the calculations of the load limit, and the last part is about the calculations of real column holdup (also known as liquid holdup). Essentially, all these parts are needed for an effective output to be real.

The paper of Billet & Schultes argue to have attained a uniform theory to determine the four abovementioned calculations. Furthermore, they claim to have physically proven their theory with sufficient experimental results, and even more they have compiled a database that includes over 3500 measured data in which they have found measurements of over seventy types of arranged and dumped packings, which should validate their research and formulas.

3.2 Model of Engel & Stichlmair

Engel & Stichlmair [2]show step by step how countercurrent flow with gas flows and liquid flows work. Firstly, they explain the fluid dynamics when using packing material. In Engel's model, the only properties of the packing material (besides the properties of the fluids of course) that are needed are the void fraction and the specific geometrical surface area. However, when the gas flows are taken into account (that is: countercurrent flow is happening), a certain specific 'experimental value' should be used for calculation in the model. This value depends on the packing material as well. However, these additional characteristic values of the packing materials seem not to be included in Rapsody's database.

Concluding, Engel & Stichlmair clearly show that there are only a few characteristics needed of the packing material for the model to work: the void fraction, the specific geometrical surface area, and the dry pressure drop constants fitting specific packing material. Engel claims to have correlated a model by using more than 1000 data points, which is less data than Billet & Schultes. Still, it validates their research equally good since the experimental data contain a lot of data points.

4 Practical use of Rapsody

For Rapsody to work, certain inputs must be given like the type of liquids and gasses, the velocities and quantities at which they enter the tank, and the pressure and temperature at which the gasses and liquids enter the tank, and the type of arranged or dumped packing material that the tank will be filled with. If all these inputs are given, one can look at what point the diameter of the tank, the hydraulic system becomes stable and thus operational. That is; the tank does not flood, but the liquid holdup becomes great enough for the gas and the liquid to interact.

Already it is obvious that a lot of decisions has to be made for a machine that washes polluted gasses before coming to decide what the measurements of the diameter of the tank should be. For example, one of these decisions could be what kind of packing material should be used, or what rate the waterflow should be.

4.1 Input of Rapsody

Rapsody's interface is clear in what kind of inputs must be given. The following inputs are required in Rapsody to say something about the fluid dynamics of the washing tank:

- **Operating Temperature**
  the temperature at which the washing process will take place.
- **Operating Pressure**
  the pressure at which the gas will be entering the tank.
- **Type of Liquid**
  various liquids have different properties, for instance their density (kg/m^3), surface tension (N/m) and viscosity (cP). These properties matter when using Rapsody.
- **Type of Gas**
  various gasses have different properties, for instance their density and viscosity.
- **Flow Rate**
  Of course the flow rate of both liquid and gas (m/s) needs to be known for Rapsody to figure out if the washing tank will be functional.
- **Packing Material**
  The packing material will be the porous medium within the washing tank. This will affect the fluid dynamics significantly. The specific properties of the packing material that matter are the surface area density a_{geo} (m^2/m^3), the void fraction ϵ (%), which were both discussed earlier in the theoretical framework of packed columns, but also the nominal packing diameter d (m) .
- **Column Diameter**
  The column diameter (m) is the diameter of the base of the washing tank. If the diameter increases, the washing tank has a smaller chance to flood.
- **Model**
  The Rapsody program is based on three different models for calculating the loading and flooding point. The user can manually choose one of these models when using Rapsody. Nevertheless, there exists an automatic option which prefers to use certain models when using certain packing materials.

4.2 Output of Rapsody

4.2.1 Flooding line

Above the flooding line, the pressure drop and liquid holdup increase exponentially, and the manual of Rapsody states that 'there is no sensible way of operating a column at or above this line, as more and more liquid is accumulating in the column until countercurrent flow is no longer possible and pressure drop increases rapidly'. Logically, Rapsody advice, just as the bundled literature does [1], to operate below this line at all times. The flooding line is expressed in capacity of liquid (m/s, horizontal axis) and in capacity of gas (m/s, vertical axis).

4.2.2 Loading line

Below the loading line, the holdup is nearly independent from the liquid and gas, so effectively the gas flow has no influence on the liquid holdup. Above this line, the increasing vapor flow causes the liquid hold up to increase. The line is close by 65% of the gas capacity of the flooding line. The loading line is expressed in capacity of liquid (m/s, horizontal axis) and in capacity of gas (m/s, vertical axis), just as the flooding line.

4.2.3 Operating point

The operating point shows at what point the design is located. This point is expressed in the same space as the loading and flooding line. In the Rapsody interface, the operating points can be translated to three different cases, belonging to the input of three different gas- and liquid flows. First, the *yellow circle* corresponds to the original design of the gas- and liquid flows. In this paper we will call this operating point the normal design. Second, the *yellow triangle* corresponds to the minimum design of the gas- and liquid flows. This operating point will be called the minimum design. Last of all, the *yellow square* corresponds to the maximum design of the gas- and liquid flows. This operating point will be called the maximum design. So when an operating point is above the flooding line, the combination of the gas flow, liquid flow, type of packing material and other input is insufficient to keep the washing tank operational. If an operating is between the loading and flooding line, it is not sure whether the washing tank will be functional. If the operating point is close to or beneath the loading line, the washing tank will be operational for the chosen input in Rapsody.

So in essention, the output of Rapsody says something about the operationalization of the washing tank that is being modelled. This means that it says nothing about how, and even if, the polluted gasses are being washed. Rapsody can only determine if the washing tank itself can be operational.

4.3 Mechanisms of Rapsody

In this part, some mechanisms of Rapsody will be explained. Naturally, when changing some variables in the Rapsody-interface, the output will adapt to these changes. We will look at what happens when changing the different parameters.

- Effect of operating temperature

When changing the operating temperature, the properties of the liquids and gases change. To be exact, the density, viscosity, and surface tension of the liquid will all decrease when the temperature increases. Also, the density of the gas decreases when the temperature increases, however the viscosity of the gas will increase. For the output of the tank this has the effect that the loading and flooding line shift a little upwards, and the operating point(s) will shift upwards as well, however they will maintain their horizontal position. When increasing the temperature (exemplum gratium, from 20 to 200), the operating points will shift upwards more than that the flooding and loading line are.

- Effect of operating pressure

When changing the operating pressure, the density of the gas will linearly increase. So, when doubling the amount of pressure, the density of the gas will double as well. On the output, this has the effect that the operating point will decrease when the pressure will be increased. However, it should be taken into account that when changing the pressure, most likely the flow rate of the gas will be attuned to this change of pressure, which will 'counter' the effect of the change in pressure.

- Effect of liquids

When changing the type of liquid, the density, viscosity, and the surface tension will of course become different. It is important to note that each of the three properties individually can have a huge impact on the fluid dynamics of the washing tank. For example, if the surface tension becomes sufficiently small, namely smaller than 10^{-3}, the flooding and loading lines both decrease, increasing the chance that the operating point lies above these lines without changing other parameters drastically (examples of liquids with small surface tension are Phosgene, Trifluoro-methane, R-13, and fluoroform). When the density of a liquid is increased, the operating point will decrease and shift to the left of the grid. The viscosity of the liquid does not affect the operating point, but it does affect the flooding and loading line. When the viscosity increases, the flooding and loading line shift downwards. Examples of high viscosity are octyl-alcohol (8,43 cP) and sulfuric acid (23,4 cP). It is logical that a higher viscosity causes the flooding and loading lines to shift downwards, as they are thicker and have more difficulty moving through the washing tank.

- Effect of gasses

When changing the type of gas, the flooding and loading line does not change. However, the operating point does change as the difference in density of gasses play an important role in the countercurrent flows. When the density of a gas is high (Rapsody considers gasses with a density of $>$ 5 kg/m3 as 'high density'), the operating points will be quicker to be below the loading and flooding line, but when the density is low, the operating point will rather be above the loading and flooding line. A good example of a gas with low density is hydrogen. However, it should be noted that the flow rate of a gas depends on the density of the gas. So therefore, when encountering high or low density gasses, the fluid dynamics can easily be compensated by adjusting the flow rate until a desirable outcome is achieved. Furthermore, in practice, the viscosity of a gas does not play a huge role in the process of countercurrent flows, since the viscosity of different gasses are close to each other in value.

- Effect of flow rates

When altering the flow rate of the liquid, the only thing that changes in the output is the operating point. When increasing the flow rate of the liquid, the operating point shifts to the right, and when decreasing the flow rate, the operating point shifts to the left. This means the operating point could end up above the flooding and/or loading line when the liquid flow rate is increased to a certain extent. When altering the flow rates of the gas, the operating point is again the only output that is affected. When increasing the gas flow rate, the operating point will go upward, when decreasing it will move downward. This also means the operating point could end up above the flooding and/or loading line when the gas flow rate is increased to a certain extent.

- Difference in models

The choice of model can have a huge impact on the output of Rapsody. Firstly, when choosing between the Mersmann or Engel & Stichlmair model, the operating point can be below the flooding line in the model of Mersmann, but above the flooding line in the model of Engel & Stichlmair. Even more, the model of Billet & Schultes shows more differences with the model of Engel & Stichlmair when using the same parameters. In Figure 3 for example, the difference between the two models is demonstrated. Whereas the model of Engel & Stichlmair shows its operating point below the loading line, the model of Billet & Schultes fixes the operating point above the flooding line. Note that both the operating points lie at the same point in the grid. Therefore, the choice of model is certainly of importance when using Rapsody.

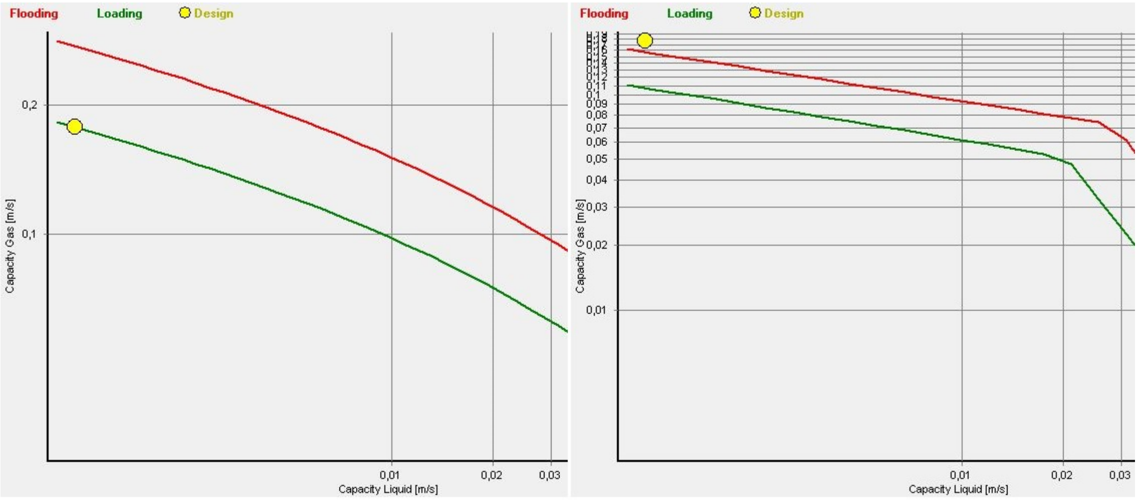

FIGURE 3: The difference between the model of Engel & Stichlmair on the left (A) and the model of Billet & Schultes on the right (B). The operating point of (A) lies below the loading line, at the most optimal point, whereas the operating point of (B) lies above the flooding line, meaning that the washing tank should not be operational at all.

- Effects of packing material

A number of things are important when using random packing material. Both the flooding and loading lines are affected by the choice of packing material in the model of Engel and Billet/Schultes. First of all, the surface area a_{geo} (m^2/m^3) is one characteristic of the packing material. When increasing the surface area of the packing material, the operating point is shifting towards the flooding and loading line (assuming all other input is fixed), meaning the lines are becoming smaller in some way. The void fraction ϵ (%) of the packing material has also an effect on the process. Higher void fraction often means that the operating point will be more likely to be below the flooding line (assuming all other input is fixed).

- Effects of column diameter

When fixing all other variables (like the abovementioned), the column diameter tells a lot about the fluid dynamics of the washing process. For example, the amount of liquid load $(m^3/m^2/h)$ is connected to the column diameter, but also the dry pressure drop and operating pressure drop $(mbar/m)$. When the column diameter is increased, the operating point shifts towards the left and downwards. So the chance for the tank to decrease will be smaller when increasing the column diameter. This is logical, since the tank becomes larger in width, and the liquid will be more easily carried away from the tank. In most cases, the column diameter will be in between 1000 and 2500 millimeters.

4.4 Optimizing the type of packing material

In his analysis on packing material, Mackowiak [1] suggests that modern lattice-type and structured packings have huge advantages in gas cleaning processes, because of their relatively high void fraction; a low void fraction can cause dead space that could be filled with liquid. This means the influence on the gas is lower, and a high void fraction is desirable in gas cleaning processes, since the liquid needs to interact with the polluted gas. The "third generation" packing material, as Máckowiak calls them, include many of these lattice-type packings with high void fraction.

Additionally, as Mackowiak mentions in his chapter Packed Columns, the resistance coefficient shows great negative effect when the ratio of the column diameter (D_C) towards the nominal packing diameter (d), that is D_C/d is lower than 5, whereas the negative effects wear off when this ratio is larger than 10. Therefore, as a rule of thumb, this ratio should always be above 10, as seen in equation 6:

$$\frac{D_C}{d} > 10. \tag{6}$$

This rule exists because otherwise the dry pressure drop will increase. However, what can not be retrieved by experimenting within Rapsody, is the form factor of packing material. The form factor represents the ratio of the open area of a packing to the closed wall. According to Máckowiak, the form factor has an influence on the resistance coefficient. Therefore it will, as mentioned earlier, have an effect on the dry pressure drop and it should be integrated in Rapsody if possible.

4.5 Case of Wieringerwerf

The alignment of the washing tank in Wieringerwerf is a typical case in which a washing tank is used to clean polluted gasses in the bio-industry. This alignment is specifically interesting because the bathing series are unusually large. The input of this setup is known:

The operating temperature of this setup is standard, namely 20 degrees Celsius. However, the operating pressure is higher then usual, namely 2 bar (instead of the usual 1). The type of liquid in this case is water, but the type of gas that needs to be washed is not yet clear for this case. Therefore we will work with dry air temporarily. The flow rates of both the liquid and gas is known. For the gas this will be 38080 kg/h (taken into account the operating pressure), and for the water the flow rate is 10250kg/h. This can all be seen in Figure 4.

The packing material will be Hiflow Kunsts 38-1 (HFP 38-1 in short), and the model that usually goes with this type of packing material is the Engel/Stichlmair model. Finally, the column diameter of the washing tank is 1500 mm. In Figure 4, most of the input can be seen on the Rapsody interface. The rest of the input can be found on Figure 5, as well as the output. It is visible that the output of the normal design, the minimum design, and the maximum design correspond to the yellow circle, the yellow triangle and the yellow square respectively. The maximum design is situated almost exactly on the loading line, which is a good sign. The normal and minimum designs are situated below the loading line. It is

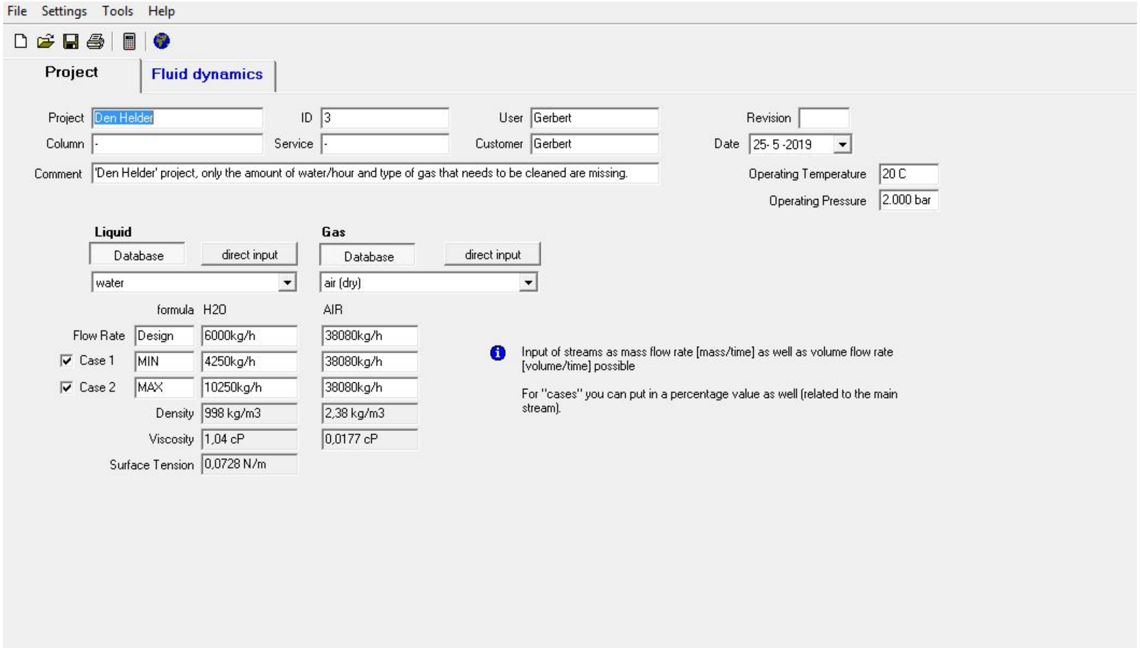

FIGURE 4: Input of the Wieringerwerf case.

safe to let the minimal point be below the loading line, but for optimization, it is a good idea to have one of the operating points slightly above the loading line at approximately 75% of the flooding line. The findings of the output are visualized in Figure 5 .

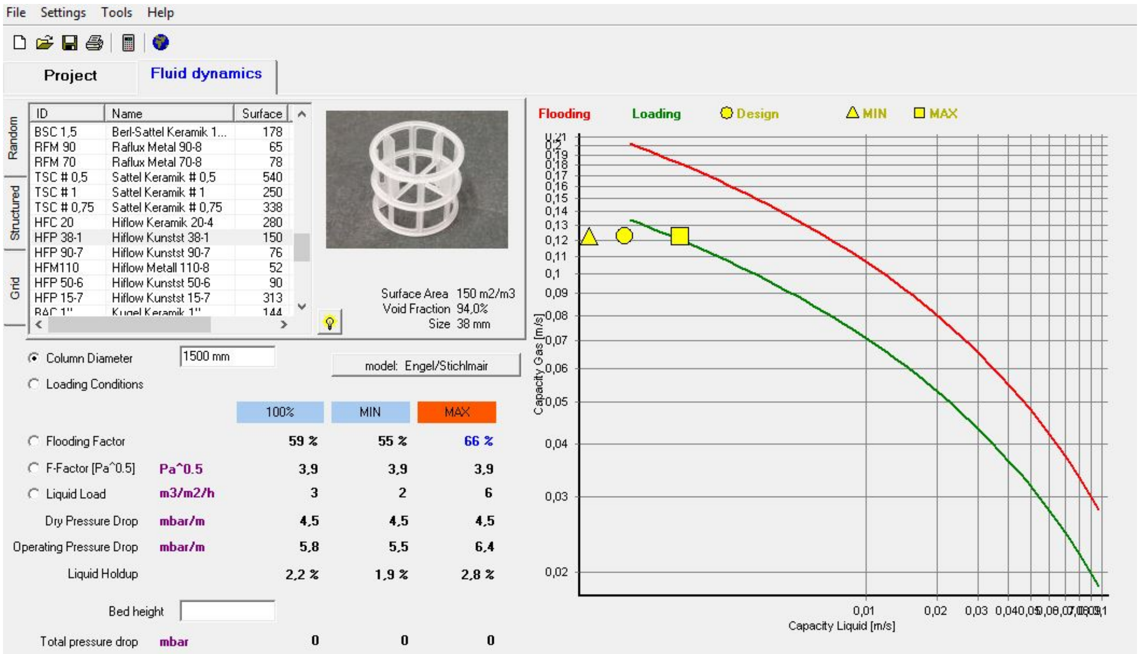

FIGURE 5: Output of the Wieringerwerf case in the Rapsody-interface, using the Engel/Stichlmair model. The yellow triangle, circle, and square represent the minimum, normal, and maximum operation points respectively.

Another point of view to the Wieringerwerf-case can be created by using the Mersmann model. In this model, the output will be different. Firstly, the loading and flooding line are given in different dimensions, but it is important to remember that all other parameters stay the same. Therefore, the loading and flooding line by Mersmann are based on different parameters than those of Billet & Schultes and Engel & Stichlmair. The minimum design is situated on the loading line, whereas the normal and the maximum design are slightly above the loading line.

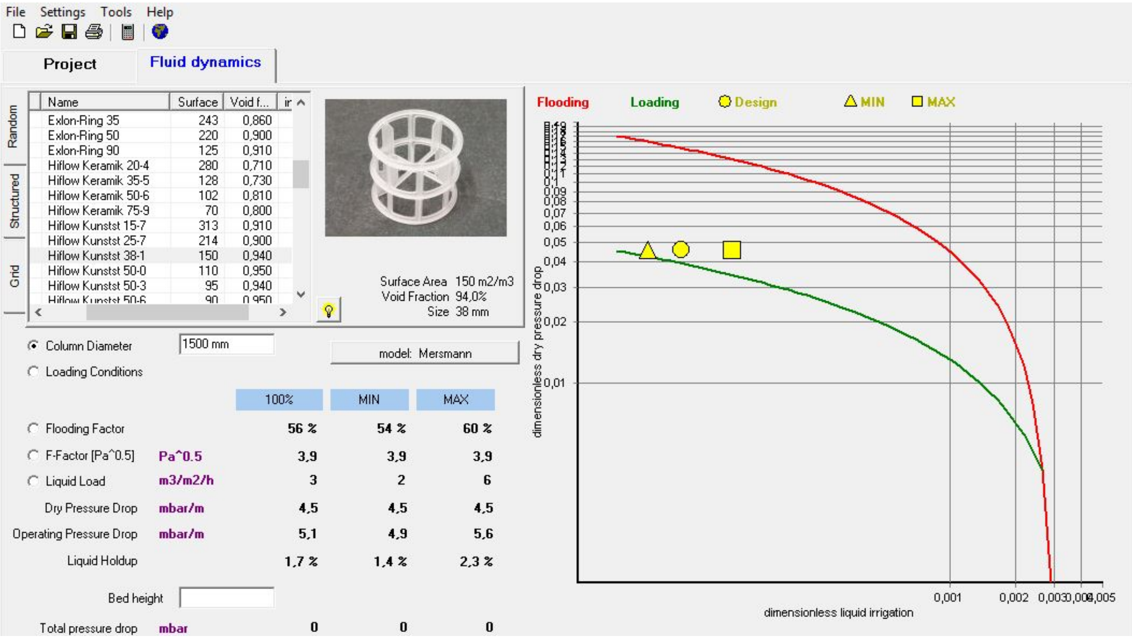

FIGURE 6: Output of the Wieringerwerf case in the Rapsody-interface, using the Mersmann model.

According to Mersmann, the minimum and normal design are close to optimal for the operationalization of the washing tank, but the Engel & Stichlmair model is slighty more optimal. However, the pressure drop in the Mersmann model is lower and therefore objectively better. In Figure 6, the output of the Mersmann model in can be found using Rapsody.

4.6 Analysis of packing material in the Wieringerwerf case

However, it is smart to look at different types of packing material and look how this changes the behavior of the fluid dynamics inside the washing tank. The HFP 38-1 is especially strong because of the safe operating points and its high void fraction. Its surface area is 150 m^2/m^3, its void fraction 94%, and its size is 38 mm. Three alternatives for the HFP 38-1 will be given.

FIGURE 7: The HFP 38-1

4.6.1 The Hiflow Ceramic 75-9

One of those options is the Hiflow Ceramic 75-9 (HFC 75 in short). The HFC 75 has very different properties compared with the HFP 38-1, for example the void fraction is 80% whereas the void fraction of the HFP 38-1 is 94%. Also the surface area of the HFC 75, 70 m^2/m^3 is more than half of the surface area of the HFP 38-1, and its size, 75 mm, is therefore twice as big as the HFP 38-1. When using the Engel & Stichlmair model, the operating points (normal, minimum and maximum design) of the HFC 75 all shift a little towards the right, towards the flooding line, making the normal design situate on the loading line, with the minimum and maximum designs being on below and above the loading line. This is probably the most optimal way for the designs to be situated. However, one of the downsides of the HFC 75 is that it has a lower void fraction than the HFP 38-1. Especially in gas cleaning occupation, a high void fraction is better for cleaning the gas. The irrigated pressure drop of the HFC 75 is significantly higher than that of the HFP 38-1 (which is not good). Therefore it is unclear whether the HFC 75 is a better choice than the HFP 38-1. In Figure 9 the output and the properties of the HFC 75 are given.

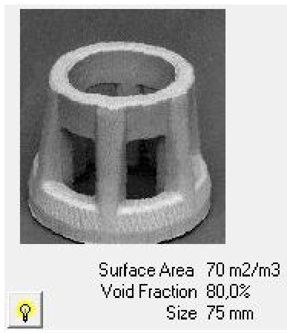

FIGURE 8: The HFC 75

FIGURE 9: Output of the Wieringerwerf case, using the HFC 75

4.6.2 The Hiflow Metal 40-5

FIGURE 10: The HFM 40

The Hiflow Metal 40-5 (HFM 40 in short) has almost the same dimensions as the HFP 38-1: a surface area density of 143 m2/m3, a size of 40 mm, and a void fraction of no less than 97%. However, its operating points are very similar to the HFC 75 when using the Engel & Stichlmair model, since its normal design is located on the loading line, and its minimum and maximum are below and above the loading line respectively. However, the irrigated pressure drop of the HFP 38-1 is significantly lower than the HFM 40. Still, because of the advantage of the operating points being on both sides of the loading line, and an even higher void fraction than the current HFP 38-1, the HFM 40 has an edge over the HFP 38-1. In Figure 11 the output and the properties of the HFM 40 are given.

FIGURE 11: Output of the Wieringerwerf case, using the HFM 40

4.6.3 The Hiflow Metal 50-5

The Hiflow Metal 50-5 (HFM 50 in short) has the same operating points as the HFP 38-1: the maximum design on the loading line and the normal and minimum designs below the loading line. With a surface area of 95 m2/m3 and a size of 50 mm, its dimensions on the other hand are slightly different. With a clearly higher void fraction of 97,8% the HFM 50 has a clear advantage over the HFP 38-1. However, the irrigated pressure drop is slightly lower when using the HFP 38-1 instead of the HFM 50. It is not clear if the HFM 50 would be a better choice than the HFP 38-1. In Figure 13 the output and the properties of the HFM 50 are given.

FIGURE 12: The HFM 50

FIGURE 13: Output of the Wieringerwerf case, using the HFM 50

4.6.4 The Raflux Metal 70-8

FIGURE 14: The RFM 70

Lastly, the Raflux Metal 70-8 (RFM 70 in short) may be a valid option for the case at Wieringerwerf. Its dimensions are different than the HFP 38-1; a surface area of 78 m2/m3, 70 mm in size, and a void fraction of 97%. The operating points of the RFM lies slightly to the right: the maximum design lies above the loading line, and the normal and minimum design lie below the loading line. The irrigated pressure drop of the RFM 70 is slightly higher than the HFP 38-1, however the liquid holdup is a lot lower than that of the HFP 38-1, which is a desirable. Eventually, because of its higher void fraction and lower liquid holdup, the RFM 70 has a slight edge over the HFP 38-1. In Figure 15 the output and the properties of the RFM 70 are given.

FIGURE 15: Output of the Wieringerwerf case, using the RFM 70

Packing material	a_{geo}	ϵ	d	D_C/d
HFP 38-1	**150** m^2/m^3	**94%**	**38mm**	**39.5**
HFC 75	70 m^2/m^3	80%	75 mm	20.0
HFM 40	143 m^2/m^3	97%	40 mm	37.5
HFM 50	95 m^2/m^3	97.8%	50 mm	30.0
RFM 70	78 m^2/m^3	97%	70 mm	21.4

TABLE 1: Properties of different packing material in the Wieringerwerf case

4.6.5 Possible improvement of packing material in the Wieringerwerf case

A couple of potential packing material were analyzed and a few types of packing material seem to be more valid choices than the current choice, the HFP 38-1. In Table 1, the properties of the packing material can be found. In the second column, the specific surface area can be seen, the third column shows the void fraction, the fourth column shows the nominal packing diameter, and the last column shows the rule of thumb that applies, using equation 6. Only the operating points are not processed in Table 1.

All of the packing material meet the requirement of equation 6, working with a column diameter of 1500 mm. The HFM 40 has a clear advantage because of its higher void fraction and more diverse operating points. Another valid choice would be the RFM 70, also because of its higher void fraction and its significant lower liquid holdup.

5 Discussion

There are a couple of research possibilities when looking at Rapsody and the construction of a washing tank. As Máckowiak mentions in Packed Columns: *'Additional information on energy-saving measures, such as optimum feed concentration, use of heat pumps, reflux ratio limitations, and bottom pressure, is given elsewhere.'* Since *CKB Kunstoffen* focuses on optimizing their workflow, it seems more than logical that a look in these directions would be beneficial, especially the part about energy-saving measures.

Furthermore, Máckowiak talks about maldistribution in random packings. He again emphasizes the important rule of thumb that the ratio of the column diameter to the packing diameter should be bigger than ten, as he says: *'The main factors that have influence on the maldistribution in random packings are the column diameter to packing diameter D_C/d ratio and the quality of the initial liquid distribution on top of the column. The distribution quality is usually characterized by the number of drip points per unit area of the column cross-section.'*

Logically, the other variables in Rapsody, the ones who should be fixed before one can make a decision about the packing material, are subject to change. For example, the velocity by which the liquid is entering the washing tank is one of them. Since the height of the washing tank and the type of pump influences this velocity, this sort of relocates the variable of liquid velocity to the height of the tank and the type of pump that is used. When specifically wanting, for example, a high void fraction in packing material, it is smart to use Rapsody before determining the height of a washing tank or the type of pump used, since this can limit the choice of packing material if the liquid velocity changes.

6 Conclusion and Recommendations

Even though Rapsody is a small part of a large workflow of making decisions, Rapsody is of great importance when determining what kind of packing material should be used in a washing tank like *CKB Kunststoffen* is producing. This workflow starts at the problem that arises: what is the best course of action? When decided that a washing tank should be built, the chain of decision-making will be initiated. First of all the quantity of polluted gasses that are to be washed needs to be known, and how these gasses will be released (chromed, nickeled, galvanized, etc.) by process baths. The installation of the process baths and extraction of the polluted gasses is by itself a challenge, when keeping in mind that this needs to be very well connected to the washing tank. The next decision will concern the dimensions of the washing tank. Questions arise like wether there are limitations to these dimensions (for example, the height of the tank cannot exceed a certain level). Together with these dimensions, other engineering parameters that play a role in the washing tank can be fixed, like pressure regulators, temperature regulators, gas flow and liquid pumps. After all these parameters are fixed, or at least most of them, Rapsody can enter the workflow. Rapsody can show detailed information about the fluid dynamics of the washing tank, and if certain parameters or a combination of parameters are fixed in no feasible way, Rapsody will make this clear. A visual representation of a generalized workflow can be found in Figure 16.

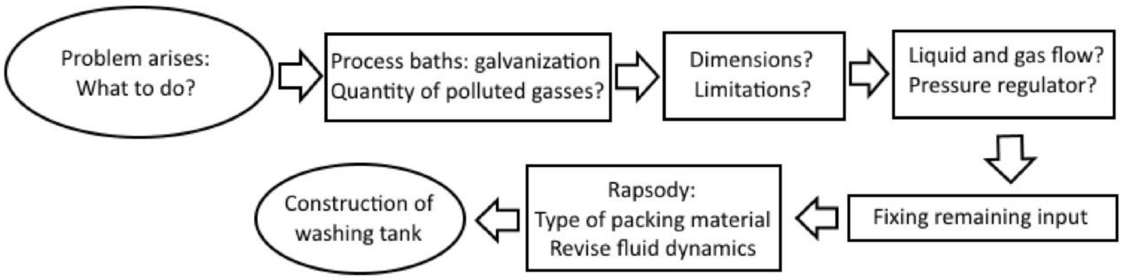

Figure 16: Example of general workflow for the operationalization of a washing tank

The most important feature of Rapsody is of course to conclude what type of packing material will fill the washing tank. Therefore it is important to fully understand what to opt for when using the Rapsody tool. The importance of pressure drop, liquid holdup, and the flooding of the washing tank are key points in its design, and when using Rapsody this should be kept in mind.

General advice in using random packings in packed columns for a washing tank, is that one should specifically keep in mind the void fraction of the packing material. A high void fraction has a clear advantage as it is a lattice-type packing and therefore extremely viable for gas cleaning processes.

Something to worry about is the fact that there exists a huge difference in output when using different models (Engel & Stichlmair versus Billet & Schultes). In some cases the difference can be so big that it is not sure if the operating point lies below the loading line or above the flooding line. Since the code of Rapsody could not be looked into, it is not clear what causes this discrepancy. The best way to tackle this problem is to 'play it safe' when using Rapsody, meaning that one should look for an operating point below close to the loading line in all the models of Rapsody.

The next thing for *CKB Kunststoffen* is to find out how clean the polluted gasses will become after being cleaned by the washing tank. An idea for this future research is to measure the pollution of the gasses before they enter the washing tank and to measure the pollution of the liquid after it has left the washing tank to find out how much pollution has transferred to the liquid. Another idea is to immediately measure the cleanliness of the gasses that leave the washing tank by, for example, capturing a fraction of the cleansed gasses in a small gas tank. When this research is completed, *CKB Kunststoffen* can truly say something about the quality of their washing tanks.

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