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Multi-cyclonic vacuum cleaners as a pedagogic case study of process intensification

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Abstract

Process intensification has emerged as a strategy to satisfy the objectives of process efficiency, sustainable development and economic competitiveness. Unfortunately, intensified technologies are too numerous to fit in a time-constrained academic syllabus. For high pedagogic impact, appropriate case studies should be favored to cover a wide range of strategies while demonstrating these opportunities, using accessible tools and concepts.

The developed case study demonstrates the gain of sustainability offered by applying multi-scale design to a cyclonic separation, enabling miniaturization at constant efficiency. The analysis leads to well-known multi-cyclonic systems. This example is particularly striking for students since multi-cyclonic vacuum cleaners are a domestic illustration of this strategy.

The analysis aims to miniaturize the separator, at constant efficiency and dissipated mechanical power. By applying a scale factor to cyclone dimensions, while maintaining the

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efficiency, a first strategy demonstrates that miniaturization alone cannot be sustainable. The best strategy considers parallel miniature cyclones, which enables to satisfy all objectives: the volume and dissipated mechanical power can be reduced simultaneously, requiring a multi-objective optimization.

Scenarios for integration of the case study in various curricula are proposed, by differentiating the learning outcomes as a function of student level and course objectives.

Key words

Process intensification, cyclone, miniaturization, collection efficiency, cutoff diameter, energy input

1. Introduction

Process intensification has emerged as a relevant strategy to satisfy various objectives for either the debottlenecking of existing chemical processes or the development of innovative processes, in a wide range of applications from industrial gases to pharmaceutical products (Hessel et al., 2009; Segovia-Hernandez and Bonilla-Petriciolet, 2016). The methods and technologies proposed for process intensification are recognized to improve process efficiency through higher chemical yield and selectivity, to increase process sustainability by significant energy savings, to strengthen economic competitiveness by reducing capital and operational expenditures, and to enhance process safety by reduction of chemicals inventory through process miniaturization and conversion of batch production to continuous flow chemistry (European Roadmap for process Intensification, 2008). Several inspiring demonstration works and success stories not only convinced the chemical engineering

community of the attainable benefits but also highlighted the reluctances and brakes to commercial implementation, for applications including organic synthesis (Krummradt, 1999; Minnich et al., 2011), ionic liquid synthesis (Bayer et al., 2005; Renken et al., 2007), gas-phase catalyzed oxidations (Lange et al., 2012) and petrochemical industries (Harmsen, 2010).

Unfortunately, this variety of potential impacts hides a complexity, which finds its origins in the diversity of the potential means of action to re-design a process or think out-of-the-box to design a new process. Since the pioneering works of Ramshaw (1995) and the reference paper and book by Stankiewicz and Moulijn (2000, 2004), numerous works and handbooks proposed accurate definitions and structured approaches, either focusing on specific classes of devices and methods, or assembling this puzzle in a Cartesian framework according to fundamental (van Gerven and Stankiewicz, 2009; Stankiewicz et al., 2019) or technical viewpoint (Reay, 2013; Commenge and Falk, 2014). Despite strong academic and industrial efforts to define and structure process intensification as a stepwise methodology, this diversity of tools and actions still leaves a part of the path out of the view of chemical engineers

Indeed, the analysis of process intensification works leads to a non-exhaustive list of 17 types of process limitations that can be reduced or even suppressed by applying appropriate strategies (Commenge and Falk, 2014). These limitations range from classical heat and mass-transfer limitations to more intricate limitations such as utilities consumption, equipment volume, dissipated mechanical energy or safety. The same analysis highlights potential strategies to overcome these limitations: specific actions at the molecular scale, the equipment scale or the process scale may be helpful to improve the overall performance of the process. The choice of the most appropriate strategy (or a combination of several strategies) is guided by heuristics, by expert tuning or by dedicated modelling and decision tools. However, the

obtained solutions are often left aside due to their unconventional character and the little feedback on these technologies, explaining the slow implementation of intensified processes at the commercial scale.

This diversity is still more challenging when the objective is to teach Process Intensification in an academic curriculum or as lifelong learning. Since the early 2000s, Process Intensification has been included in numerous chemical engineering curricula, in Europe and worldwide (Dietrich, 2009). Rivas et al. (2020a, 2020b) present a thorough review of these challenges and analyse not only the adequacy between the learner skills and the expected outcomes but also the content and learning activities that should be favoured for highest efficiency. To fully appreciate the relevance of Process Intensification, a good knowledge of most-common unit operations and the underlying sciences is necessary, as well as a certain familiarity with plant-wide approaches (Process Synthesis, Process System Engineering). Lists of intensified devices and multi-functional couplings are ineffective since intensified technologies are too numerous to fit in a time-constrained academic syllabus, and since they do not show the methodological aspects that open so many degrees of freedom and innovative solutions. Creative activities are advised to immerse the learners in a proactive construction of the solution, by trial and error, and by comparison of various strategies at different scales.

For high pedagogic impact, appropriate case studies should be favored to cover a wide range of strategies while demonstrating these opportunities, using accessible tools and concepts. Dedicated contents, exercises and problems have been developed by academic teams to facilitate education on this subject: Supplementary information in Rivas et al. (2020b) provides numerous examples of taylor-designed contents such as homework problems, direct application exercises for individual training or more complex problems for group activities and challenge-based learning.

The present work details a single case study that can be submitted for individual or group work in a limited time constraint without requiring any numerical tool except a basic calculator. Its pragmatic advantage is the possibility to quickly test and compare various strategies to improve the efficiency and sustainability of a gas/solid separation. Its pedagogic advantage is the possibility of multiple contextualization since it can either be presented as a demonstration of the structure of industrial large-scale cyclonic systems, or as an illustration of the innovative design of everyday life multi-cyclonic vacuum cleaners.

The next sections first present the case study, the performance objectives from a technical and sustainable point of view, the design rules for this type of separation equipment, the reference process design and the possible strategies to intensify the process. Then, the strategies are developed and compared with appropriate figures, and further developments are proposed to enlarge the problem or to adapt it to specific contexts. The final section helps educators to integrate this case study in engineering curriculum by discussing prerequisites, learning outcomes and preferential formats, according to two integration scenarios.

1. Description of the case study

1.1. Objectives of the case study

The objective of this case study is to intensify the operation a cyclonic gas/solid separation and improve its sustainability, while maintaining its overall performance and productivity (for a fixed feed flow rate and composition), by applying appropriate intensification strategies. Figure 1 presents a schematic view of the separation unit principle. The gas containing the particles to separate is fed through a tangential inlet at the top of the device body, composed of an upper cylindrical section and a lower conical section. Inside the chamber, centrifugal forces tend to draw particles towards the outer wall and gravity forces attract particles toward the lower conical part that guides them to the solid outlet at the bottom of the cone. The gas

with residual fine particles leaves the unit through a central outlet at the top of the cylindrical section.

The performance of such a device is characterized by a separation efficiency, called the collection efficiency, related to the fraction of the entering solid that leaves the unit by the lower outlet: the lower the fraction of residual solid in the upper gas outlet, the higher the efficiency of the device. Unfortunately, this separation requires mechanical power to generate the vortical flow and enhance centrifugal forces required for the separation. This dissipated mechanical power is lost and cannot be recovered.

Intensification of this separation unit can be explored by referring to the four-item definition proposed by Stankiewicz and Moulijn (2000):

1. Improve the production quality: the quality of this separation unit refers to its collection efficiency. Proposed intensification strategies should increase this efficiency, or at least maintain its value.
2. Reduce the size/capacity ratio: since the feed flow rate is fixed, a decrease in this ratio is synonymous with a decrease in the size of the device. Intensification strategies should preferentially miniaturize the cyclone.
3. Reduce the energy consumption: the energy consumption of the device results from the dissipated mechanical power in the vortical flow. Strategies should therefore reduce or minimize this power.
4. Reduce waste: the cyclone unit generates no waste, except residual solid in the gas outlet, already considered in the collection efficiency, and the dissipated power considered above. This item is thus not applicable for this case study.

To reach the case study objectives, proposed intensification strategies should therefore aim at increasing the collection efficiency and decreasing the unit volume and mechanical dissipated

power. The analysis can target these three objectives independently or simultaneously, highlighting the multi-objective feature of this simple problem. Each criterion has now to be quantified with relevant design rules, keeping in mind the pedagogic objective of this application.

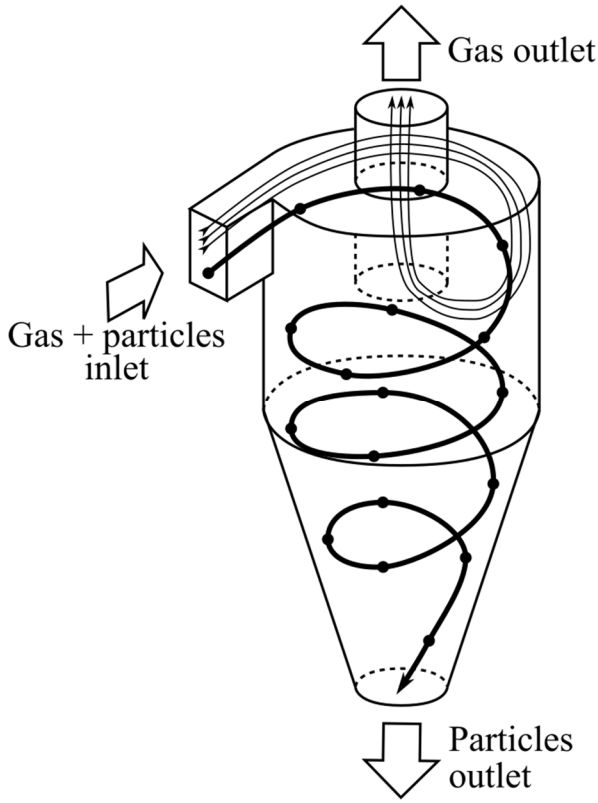

Figure 1 : Schematic view of the cyclonic gas/solid separation unit.

1.2. Design rules for cyclones sizing

The sizing of cyclone units was extensively studied and numerous correlations are available. These design rules consider the criteria of interest for the present case, the collection efficiency and the dissipated mechanical power, and many other features that are beyond the scope of this case study. Cortes and Gil (2007) present an accessible review of these approaches and relate the various correlations sets to physical phenomena and selection criteria. These correlations mainly consider the gas and solid particle properties, as well as the operating conditions and cyclone geometry as input parameters. A precise choice of

correlation is a hard task due to the variety of cyclone types and the sensitivity of the results to geometric parameters (Dirgo and Leith, 1985; Ramachandran et al., 1991; Kuo and Tsai, 2001).

To keep the exercise at a reasonable level of difficulty, the influence of the geometrical parameters should be reduced. This is made possible by considering a reference geometry, called the Stairmand cyclone, described below, whose geometric dimensions are all related to one unique geometrical parameter through constant ratios (Figure 2). The complexity of the correlations should also be sufficient for catching the main physical phenomena while being short enough for further analytical development. For these reasons, the set of correlations proposed by Kuo and Tsai (2001) was retained: the use of other sets will be discussed below as a potential extension. This sought-after and claimed simplicity is to be balanced against the variability of the results from the study of cyclones: as mentioned by Cortes and Gil (2007), the interpretation of pressure drop data is difficult and accuracy below 20 % is difficult to achieve.

The first criterion to estimate is the overall collection efficiency, defined as the fraction of the inlet flow rate of solid particles that are separated from the gas flow rate (Cortes and Gil, 2007). Nevertheless, since the particles may exhibit wide diameter distributions, it is more convenient to sort the particles as a function of their diameter and define fractional efficiencies with respect to these classes of diameter. The overall efficiency is then calculated from the diameter distribution of the particle and the fractional efficiency. The fractional efficiency η for a particle diameter Dp is calculated as:

$$\eta(D_p) = \frac{1}{1+\left(\frac{D_{p,50}}{D_p}\right)^2} \quad (1)$$

Where $D_{p,50}$ denotes the cutoff diameter, i.e. the particle diameter corresponding to 50% collection efficiency. This characteristic diameter can be expressed as a function of the gas and solid properties, the geometry of the cyclone and the feed flow rate as:

$$D_{p,50} = 3\sqrt{\frac{\mu_g b}{2\pi\rho_p U_{in} C N_t}} \tag{2}$$

$$N_t = \frac{\tau U_{in}}{\pi D} \tag{3}$$

$$\tau = \frac{V}{Q} \tag{4}$$

where μ_g denotes the gas dynamic viscosity, b the width of the tangential flow inlet (see Figure 2), ρ_p the particles density, U_{in} the gas velocity at the cyclone inlet, C a slip correction factor ($C \approx 0.01$), N_t the number of turns/revolutions made by the gas within the cyclone, D the reference diameter, V the cyclone volume and Q the volumetric flow rate.

The second criterion of interest is the dissipated mechanical power. Two sources of power dissipation are usually included in the estimation of the pressure drop: a first part is mainly due to the gas carrying a low fraction of solid particles (diluted conditions) and a second part results from the collisions between solid particles. This second contribution is neglected in this case study. Under these assumptions, the dissipated power within the cyclone is calculated as:

$$P = Q.\Delta P \tag{5}$$

$$\Delta P = 0.006\frac{\rho_g \pi D(a+b)U_{in}^2}{ab}N_t \tag{6}$$

1.3. Reference design of the Stairmand cyclone and operating conditions

To increase the educational impact, the reference case and operating conditions are fixed to ease the comparison of the results with everyday life products including cyclone units: the multi-cyclonic vacuum cleaners. The gas phase is therefore constituted of air at ambient

conditions (ρ_g = 1 kg/m^3; μ_g = 10^{-5} Pa.s). The particles exhibit a density ρ_p equal to 2000 kg/m^3 and their characteristic diameter is about a few tens of micrometres.

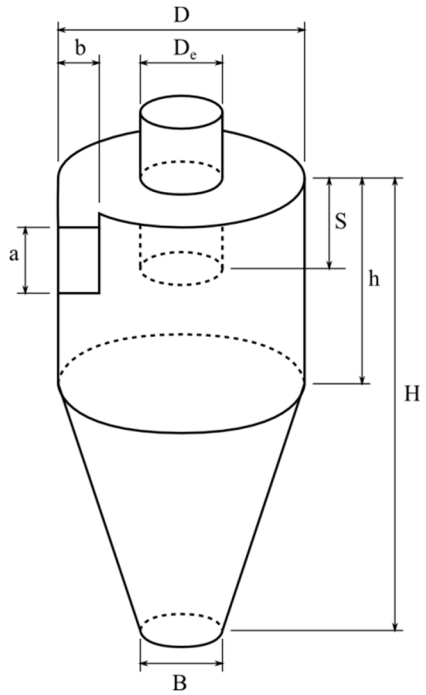

Figure 2 : View of a Stairmand-type cyclone with geometric parameters expressed as a function of the reference diameter D: a = 0.5 D; S = 0.5 D; D_e = 0.5 D; b = 0.2 D; h = 1.5 D; H = 4 D; B = 0.375 D.

The geometry of a Stairmand cyclone is illustrated in Figure 2: eight geometric ratios fully determine its shape. Its size and volume are fixed by choosing the diameter D of the cylindrical part. For this reference design, the retained diameter is 13 cm, and the operating flow rate is 50 L/s, but can be adjusted at will.

On this basis, the above expressions yield to the particle cutoff diameter, collection efficiency and mechanical power of the base case design:

- The volume of the cyclone is V_{ref} = 3.9 L,
- The gas space time is $\tau_{ref} = 0{,}078\ s$,
- The gas velocity at the feed inlet is $U_{in,ref} = 29{,}58\ m/s$,
- The number of revolutions of the gas in the cyclone is $N_{t,ref} = 5{,}6\ rounds$,

- The cutoff diameter is $D_{p,50,ref} = 10{,}6\ \mu m$,
- And the dissipated power is $P_{ref} = 32{,}6\ W$.

1.4. Possible intensification strategies

This reference design should then be modified to reach the intensification objectives: volume reduction, efficiency increase and decrease in the dissipated power. Depending on the educational context and available time, the learners can be oriented or let free to propose strategies: handbooks and publications mentionned above can be inspirational sources for listing potential strategies or for initiating brainstorming sessions. For concision, three main strategies are detailled here. They enable to gradually increase the level of complexity of the required analysis:

- Increasing the efficiency of the reference design: can the collection efficiency be increased without design modification ?
- Reducing the volume at fixed performance: can the system be miniaturized without any loss of separation performance (efficiency and dissipated power) ?
- Reducing the volume at improved performance by parallelizing cyclones: can all criteria be improved simultaneously ? Despite its relevance, this last strategy is difficult to imagine from scratch, except if images of multi-cyclonic have been fortunately presented to learners.

2. Application results and comparison of the intensification strategies

2.1. First strategy: increasing efficiency at fixed geometry

This first strategy is useful for the learner to better understand the relations between process parameters and performance criteria, especially the relation between efficiency and cutoff

diameter. The objective is to increase the efficiency without any change in the cyclone geometry.

Figure 3 presents the evolution of the fractional efficiency as a function of the particle diameter for various cutoff diameters, as given by equation (1). For a given cutoff diameter, the efficiency ranges from 0 for small particles that are not separated and leave the cyclone with the gas, up to 1 for large particles that quickly fall down in the core of the cyclone. For a given particle diameter, the fractional efficiency increases when the cutoff diameter decreases. As a result, for a given size distribution of the entering particles, the overall collection efficiency is improved by reducing the cutoff diameter. This direct relation is important for the analysis of the following strategies since it demonstrates that the cutoff diameter evolution is sufficient to discriminate between strategies that exhibit a positive or negative impact on the efficiency.

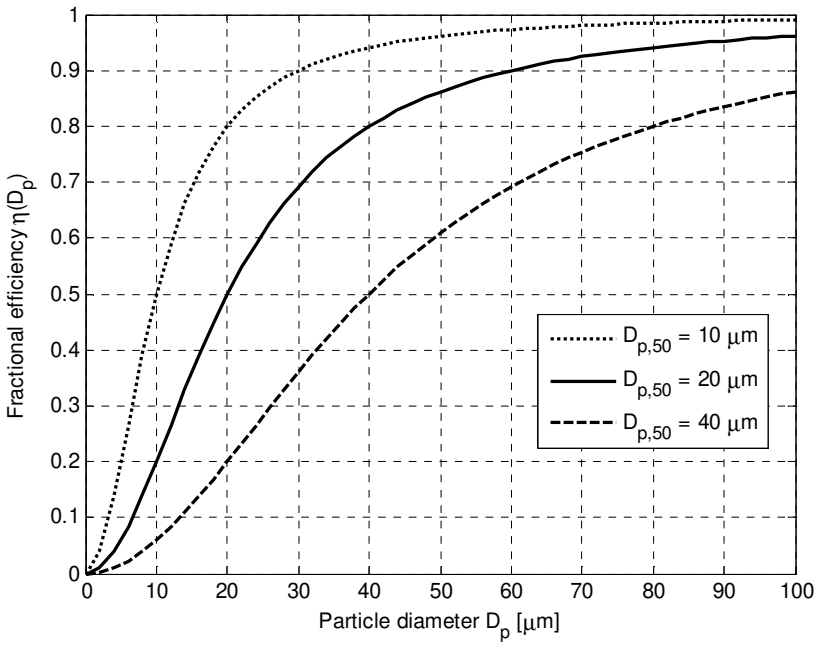

Figure 3 : Evolution of the fractional efficiency as a function of the particle diameter for various cutoff diameters.

This strategy should therefore manage to decrease Dp_{50}. Combining equations (2), (3) and (4), and relating the entering flow rate to the inlet velocity as $Q = abU_{in}$ gives an expression of the cut-off diameter:

$$D_{p,50} = 3\sqrt{\frac{\mu_g ab^2 D}{2\rho_p CV}}\sqrt{\frac{1}{U_{in}}} \quad (7)$$

The first square root of this expression only contains physical properties and geometrical parameters that cannot be modified by the current strategy. The second square root contains the degrees of freedom to reach the intensification objectives: the only possibility consists in modifying the gas inlet velocity. The gas velocity and flow rate should therefore be increased to reduce the cutoff diameter.

Unfortunately, according to equations (5) and (6), an increase in the gas flow rate induces an increase in the pressure drop within the cyclone and a drastic increase in the dissipated mechanical power. As a conclusion, this strategy is not satisfactory since it does not enable to conciliate the intensification objectives (efficiency increase) and the sustainability increase (power reduction).

2.2. Second strategy: miniaturization at fixed productivity

The second strategy aims at reducing the cyclone volume while maintaining the collection efficiency, and if possible maintaining or even reducing the dissipated power. To quantify the impact of miniaturization on the criteria, a scale factor α is applied to all dimensions of the reference design. The 8 geometric parameters of the Stairmand design become:

$$\begin{cases} a = \alpha . a_{ref} \\ S = \alpha . S_{ref} \\ D_e = \alpha . D_{e,ref} \\ b = \alpha . b_{ref} \\ h = \alpha . h_{ref} \\ H = \alpha . H_{ref} \\ B = \alpha . B_{ref} \\ D = \alpha . D_{ref} \end{cases} \tag{8}$$

As result, the volume of the miniaturized, V, is directly related to the reference volume, V_{ref}, as:

$$\frac{V}{V_{ref}} = \alpha^3 \tag{9}$$

According to equation (2), the ratio of the new cutoff diameter to the reference one can be simplified as:

$$\frac{D_{p,50}}{D_{p,50,\mathrm{ref}}} = \sqrt{\frac{b}{b_{ref}} . \frac{U_{in,ref}}{U_{in}} . \frac{N_{t,ref}}{N_t}} \tag{10}$$

In this expression, the ratio of geometric parameters b and b_{ref} is equal to the scale factor α. Since the miniaturized and reference cyclones operate at the same gas flow rate, and since this flow rate is the product of the inlet cross section by the inlet velocity, the ratio of inlet velocities $U_{in,ref}$ and U_{in} is proportional to the square of the scale factor. A similar development can be applied to the numbers of revolutions according to equation (3), indicating that this ratio is equal to unity: surprisingly, the number of revolutions is not impacted by the miniaturization. Combining these ratios yields:

$$\frac{D_{p,50}}{D_{p,50,\mathrm{ref}}} = \alpha^{3/2} \tag{11}$$

According to equations (5) and (6), the dissipated power can be rapidly analysed by introducing similarity ratios such as:

$$\frac{P}{P_{ref}} = \frac{Q}{Q_{ref}} . \frac{D}{D_{ref}} . \frac{(a+b)}{(a_{ref}+b_{ref})} . \frac{a_{ref} b_{ref}}{ab} . \frac{U_{in}^2}{U_{in,ref}^2} . \frac{N_t}{N_{t,ref}} = \frac{1}{\alpha^4} \tag{12}$$

These three criteria ratios, presented in Figure 4, then enable to conclude on the relevance of this strategy. First, the volume ratio demonstrates that a decrease in the volume requires a scale factor lower than unity. This ratio implies then that the ratio of cutoff diameters is also lower than unity: miniaturization reduces the cutoff diameter, which influences favourably the collection efficiency. The miniaturized cyclone is more efficient than the reference design. Unfortunately, a low scale factor drastically increases the power ratio: operating this miniaturized cyclone would necessitate a significant increase in the energy consumption, which is not acceptable with respect to our objectives.

As a conclusion, this second strategy is not relevant despite some interesting features related to the size of the cyclone.

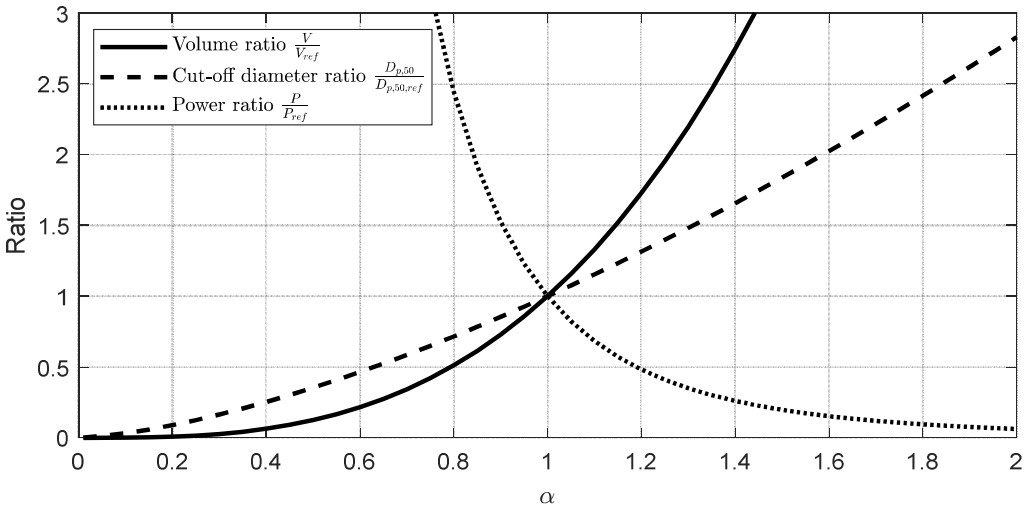

Figure 4 : Evolution of the ratios of volume, cutoff diameter and dissipated power as a function of the scale factor α for the second strategy.

2.3. Third strategy: miniaturizing and increasing productivity

The third strategy intends to take advantage of the positive impact of miniaturization observed through the application of the previous strategy, while reducing or eliminating the detrimental impact observed on the required power. Several specific strategies are known to address

specifically this issue (Commenge and Falk, 2014): one of them consists in parallelizing units to reduce the volume flow rate through each of the parallel units.

Since the analysis of this strategy contains several traps, Figure 5 clearly presents the modified process configuration. Each miniature cyclone of this strategy is again a smaller copy of the reference cyclone, characterized by a scale factor α, exactly as in the previous strategy. By comparison with the reference case, the total feed flow rate Q_{ref} is divided to feed equally each of the N miniature cyclones, characterized by identical volumes V, cutoff diameters $D_{p,50}$ and dissipated powers P. To estimate properly the performances of this strategy, particular attention should be drawn to the intensive or extensive nature of the variables: the total volume of the new configuration, V_{tot}, is the sum of the volumes of the N cyclones. Similarly, the total dissipated power must be summed up over the N cyclones. On the contrary, the total collection efficiency and the cutoff diameter are intensive features: the collection efficiency of the overall process is equal to the efficiency of one single cyclone.

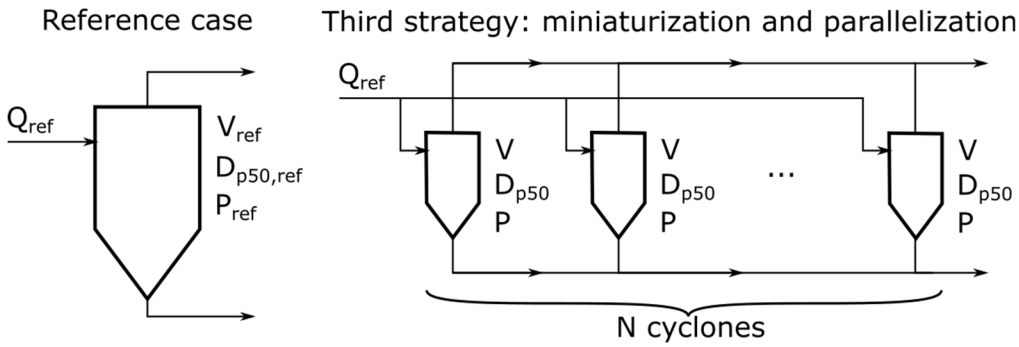

Figure 5 : Illustration of the third strategy.

By taking these precautions, one can express the total volume of the system, V_{tot}, the cutoff diameter, $D_{p,50}$ and the total dissipated power, P_{tot}, as a function of the scale factor α and the number of parallelized cyclones, N. To ease readability, the demonstrations of these expressions are given in appendix. The final expressions are:

$$\frac{V_{tot}}{V_{ref}} = N\alpha^3 \tag{13}$$

$$\frac{D_{p,50}}{D_{p,50,ref}} = \sqrt{N\alpha^3} \tag{14}$$

$$\frac{P_{tot}}{P_{ref}} = \frac{1}{N^2\alpha^4} \tag{15}$$

These expressions of the performance criteria then enable to estimate the relevance of this strategy. The objective of miniaturization can be reached if the number of cyclones N and the scale factor α are fixed so that the product $N\alpha^3$ remains lower than unity. In that case, the ratio of cutoff diameters is also lower than unity. The new cutoff diameter is therefore lower than in the reference design and the new configuration exhibits a higher efficiency. The new design thus also satisfies the efficiency criterion.

To estimate the possibility of also satisfying the power criterion, its expression can be written as:

$$\frac{P_{tot}}{P_{ref}} = \frac{1}{N^2\alpha^4} = \left(\frac{1}{N\alpha^3}\right)^2 \alpha^2 \tag{16}$$

which lets the product $N\alpha^3$ appear explicitly. This product is lower than unity, indicating that its squared reciprocal is above unity. However, if the scale factor α is sufficiently low, the product by α^2 is still below unity. As a result, there exists couples of values N and α that also enable to reduce the total power, but these design parameters must be chosen simultaneously.

To visualize and identify the possible values of N and α that enable to satisfy the three criteria on volume, efficiency and power, the isovalues of the normalized criteria can be drawn on (N; α) maps. For each criterion given by equations (13) to (15), there exists an iso-value curve (ratio value equal to unity) that divides the (N; α) plane in two zones where the ratio is respectively below or above unity. Figure 8, Figure 9 and Figure 10 of the appendix present the three detailed maps that can be used advantageously as abacuses to avoid repetitive

calculations. Figure 6 presents a synthetic overlapping of the three maps and enables to identify simply the recommended or forbidden values of α and N.

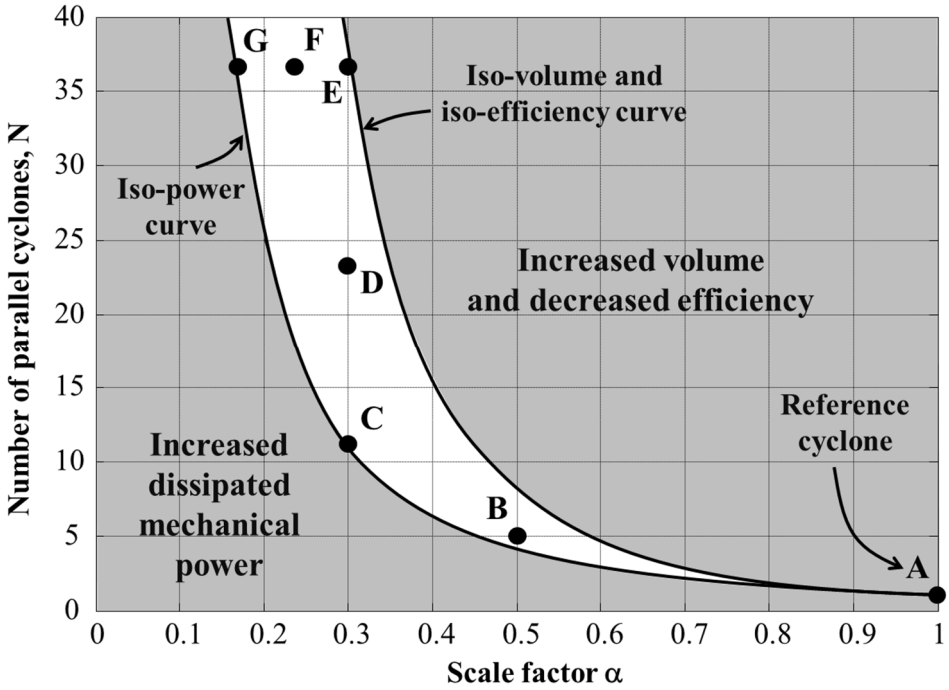

Figure 6 : Overlapping of the three criteria maps giving the volume ratio, the cutoff diameter ratio and the power ratio as a function of the scale factor α and the number of parallel cyclones N.

Two distinct curves appear in Figure 6 that correspond respectively to the iso-power curve and iso-volume/iso-efficiency curve. One should note that the volume ratio (equation (13)) is the square of the cut-off diameter ratio (equation (14)): as a result, both ratios are characterized by the same unitary iso-value curve on this map. These two curves divide the (N; α) plane in three sections:

- For small scale factor and few cyclones (lower left corner), the volume can be reduced and the efficiency can be increased, but the dissipated power increases by comparison to the reference design: this grey-shaded zone in Figure 6 is not appropriate for sustainable intensification of the considered system.

- For values of α slightly below 1 and many cyclones (upper right corner), the dissipated power is very low but the volume is large and the efficiency is reduced: this grey-shaded zone is therefore not recommended.
- Fortunately, there exists a valley between these zones where all three criteria are improved simultaneously. Seven particular designs, noted A to G, along this intensification valley are studied quantitatively in Table 1.

Table 1 : Values of the criteria for 7 possible designs enabling to satisfy all intensification objectives.

Design	Number of cyclones N	Scale factor α	$\frac{V_{tot}}{V_{ref}}$	$\frac{D_{p,50}}{D_{p,50,ref}}$	$\frac{P_{tot}}{P_{ref}}$
A	1	1	1	1	1
B	5	0,5	0,62	0,79	0,64
C	11	0,3	0,29	0,55	≈ 1 (1,02)
D	23	0,3	0,62	0,79	0,23
E	37	0,3	1	1	0,09
F	37	0,24	0,51	0,71	0,22
G	37	0,165	0,17	0,41	≈ 1 (0,98)

Among these 7 designs, the design A, with N = 1 and α = 1 corresponds to the reference design of the Stairmand cyclone and lies therefore at the intersection of the iso-power and iso-volume/iso-efficiency curves. The design E exactly lies on the iso-volume/iso-efficiency curve and therefore exhibits volume ratio and cutoff diameter ratios equal to 1. The designs C and G lie approximately on the iso-power curve (exact matching would require nonsensical number of digits) and therefore power ratio close to unity. For each of these boundary

designs, the relaxed criteria can be very low: design E enables a ten-fold decrease in the dissipated power, and design G induces a five-fold decrease in the total volume. With a number of parallel cyclones below 40, the gains do not exceed a ten-fold factor, but larger values of N enable to reach such objectives. Other designs within the intensification valley enable to improve all three criteria simultaneously but within a more modest amount. Designs B, D and F demonstrate that 30, 40 or 50 % reduction in the volume and dissipated power are achievable by appropriate combination of miniaturization and parallelization.

Because of the multi-objective nature of this problem, none of these designs can be considered optimal with respect to the others without the definition of a compromise criterion or a weighing of the criteria. However, all these designs possess a common feature: many smaller cyclones operated in parallel are a relevant strategy to intensify gas-solid separation units. This trend, deduced from the design rules of this operation unit, can be put in perspective by monitoring the market of multi-cyclonic vacuum cleaners whose number of parallel cyclones regularly increases since the 1990s.

2.4. Comparison of the strategies

Table 2 summarizes the design and operating conditions studied during the application of the three strategies and resumes their impacts on the performance criteria.

Table 2 : Comparison of the impacts of the designs and operating conditions on the performance criteria for the three strategies studied.

		Reference	First strategy	Second strategy	Third strategy
Design and operating conditions	Cyclone diameter	D_{ref}	D_{ref}	αD_{ref}	αD_{ref}
	Numbers of cyclones	1	1	1	N
	Flow rate	Q_{ref}	$> Q_{ref}$	Q_{ref}	Q_{ref}
Criteria	Volume	V_{ref}	V_{ref}	$\alpha^3 V_{ref}$	$N\alpha^3 V_{ref}$
	Cut-off diameter D_{p50}	$D_{p,50,ref}$	$< D_{p,50,ref}$	$\alpha^{3/2} D_{p,50,ref}$	$N^{1/2}\alpha^{3/2}D_{p,50,ref}$
	Collection Efficiency	η_{ref}	$> \eta_{ref}$	$> \eta_{ref}$	$> \eta_{ref}$
	Mechanical power	P_{ref}	$\gg P_{ref}$	$\alpha^{-4} P_{ref}$	$N^{-2}\alpha^{-4} P_{ref}$

From a general point of view, only the third strategy seems convincing since it is the only strategy that allows satisfying all criteria simultaneously: volume reduction, efficiency increase and power decrease. However, this multi-objective performance is obtained at the cost of a more complex process configuration and this complexity arises new questions about the feasibility of this parallelized process: the impact of a non-uniform flow distribution among the parallel cyclones can even be considered as a possible extension of this case study (see section 3.3).

The comparison of these strategies in Table 2 also highlights the increase of degrees of freedom with the increasing complexity of the process. Considering miniaturization with the second strategy introduced the scale factor α as the main degree of freedom. The parallelization of the third strategy introduced the number of cyclones, N, as a second degree

of freedom for the system design. These two degrees of freedom made possible to satisfy simultaneously the three criteria, which is a common observation in process design but should not be blindly generalized since this matching strongly depends on the dependencies between criteria and variables. As proposed by extensions in the next sections, others degrees of freedom can be explored to satisfy all criteria while maintaining the complexity of the process at a reasonnable level.

3. Possible extensions and developments

The three strategies presented in the previous section are a first possible application of this case study in a tutored time-constrained context. This basis can be adapted or extended for example validation or for further exploration of specific strategies in problem-based or challenge-based learning formats. The following sections illustrate extension proposals.

3.1. Refinement of the multi-objective analysis

The last strategy enabled to identify a valley of possible designs in the (N; α) plane to satisfy all criteria. Whereas this multiplicity of solutions is interesting from an engineering point of view, it can be frustrating for the learners who feel they have not completely solved the problem. So as to focus on one unique final solution, constraints have to be added to the research space and/or criteria.

Upper and lower bounds can easily be considered on the scale factor α and the number of cyclones N, which enables to reduce the research space in the (N; α) plane but does not suppress the multi-objective feature of the criteria. The criteria can also be constrained to reduce the size of the authorized area: minimum/maximum values of the volume or power ratios will move the boundaries of this zone and reduce the possibilities, but these boundaries will still define a tighter valley with multiple solutions. Another possibility consists in

transforming the multi-objective problem in a single optimization problem by weighing the performance criteria and combining them in a single global criterion. The difficulty then lies in the choice of the weights but can be the source of an interesting discussion with the learners. An example global criterion could be an economic criterion including capital expenditures thanks to the cyclones volumes and operational expenditures via the required power.

3.2. Impact of the cyclone shape on the intensification criteria

The generalist nature of this case study suffers from two simplifications that enabled to explore various strategies within a limited-time constrain. Firstly, the Stairmand design was considered and its shape was fixed, reducing the number of geometrical parameters to its only diameter. Secondly, the expression of the fractional efficiency was chosen for its simplicity (flight time approach) whereas more advanced representations of the physical phenomena are available in the literature (static particle approach and fractional efficiency approach).

Using the same set of equations as above, the first assumption can be relaxed by studying separately the impact of the geometric parameters a and b, that define the inlet cross section, in addition to the cyclone diameter D (equations (1) to (6) and Figure 2). The second strategy will then consider three scale factors on a, b and D respectively, whereas the third strategy will consider 4 parameters to be discussed. In addition to the difficulty related to the new dimension of the research space, additional constraints should be introduced to keep the design physically compatible with the shape of a cyclone: Ramachandran et al. (1991) and Cortes and Gil (2001) present a large panel of cyclone designs to define the ranges of geometric parameters. To explore the strategies, computers should be provided to learners or the case study should be proposed as problem-based learning or project group work.

Both assumptions can be relaxed by modifying the set of equations (1) to (6) to refine the analysis and introduce additional degrees of freedom. Works by Dirgo and Leith (1985), Ramachandran et al. (1991), Cortes and Gil (2001) and Kuo and Tsai (2001) propose different sets of expressions whose complexity can be drastically increased.

3.3. Impact of flow distribution on the multi-cyclonic configuration

The third strategy with parallel cyclones opened a perspective of extension of the problem by assuming that the inlet flow was uniformly distributed over all the cyclones. This assumption seems natural, but highly-parallel processes (defined according to the numbering-up principle) are known to be sensitive to the quality of the flow distribution. Depending on the involved phenomena, an uneven distribution is likely to create hot spots or to reduce reaction selectivity: the impact can be so large that it annihilates the expected gains.

Taking into account the flow distribution therefore seems interesting to test the sensitivity of the design, i.e. its robustness with respect to flow distribution. Unfortunately, quantifying the impact of an uneven distribution cannot be performed by simple power law ratios and requires computing the performance criteria for a given flow distribution, or for a large set of random flow distributions. For a fixed scale factor α and number of cyclones N, a possible computing sequence should:

1. Generate a list of N pseudorandom strictly positive scalar values and normalize them so that their mean equals one. Multiply this list by Q_{ref} to generate the list of flow rates through the N parallel cyclones,
2. Calculate the standard deviation of the list of flow rates and store this value,
3. For each cyclone in the list:
    a. Calculate the space time, number of revolutions, cutoff diameter and efficiency according to equations (1) to (4),

b. Calculate the pressure drop and dissipated power according to equations (5) and (6),

4. Calculate the total dissipated power by summing over the parallel cyclones,
5. Calculate the overall collection efficiency by averaging the individual efficiencies weighted by the fractions of the total flow rate through each cyclone,
6. Record these results and go back to step 1 to calculate the impact of another flow distribution,
7. Once a sufficiently high number of flow distributions is computed, plot the dissipated power and collection efficiency as a function of the standard deviation of the flow distribution.

This plot is characterized by a known limit value when the standard deviation tends to zero since the dissipated power and efficiency then correspond to the assumption of uniform flow distribution considered in the third strategy above. The dispersion of the values and their trends as a function of the increasing flow deviation can then be discussed to estimate the robustness of this design to the flow distribution. This simple stochastic sequence can be applied advantageously to introduce Monte-Carlo methods and statistical distribution to accelerate the computation.

3.4. Comparison with examples of multicyclonic vacuum cleaners

The last proposed extension of this case study is more precisely a type of validation of the observed results, especially concerning the third strategy. Indeed, the conclusions of this strategy can be compared to everyday life examples, through the commercial catalogues of multi-cyclonic vacuum cleaners available on the market. The strategy indicated that increasing the number of parallel cyclones while reducing their size is appropriate to maintain the separation efficiency and reduce the total volume and power. If this conclusion is relevant,

this trend should appear in the evolution of commercial applications of this separation principle.

For most learners, the most famous manufacturer of cyclonic systems (if not the only one they are able to quote), is for sure the Dyson company. The fame of this company and its innovating nature have drawn much attention from the public and many data are available through their commercial website (Dyson company, 2021), spare parts sellers, and technologists (Dyson products, 2021). These data give access to the number of cyclones included in the successive models sold along the years. The volumes of the cyclones are hardly accessible since exploded views or partial production plans would necessitate a long work for data extraction.

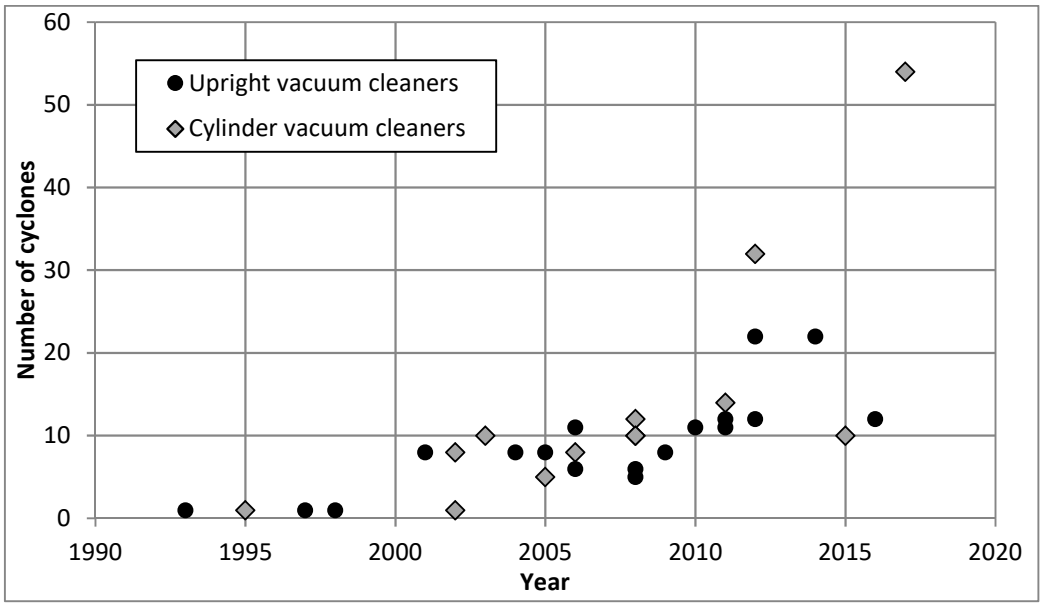

Figure 7 : Evolution of the number of cyclones included in two categories of commercial vacuum cleaners as a function of time.

Figure 7 presents the evolution of the estimated number of cyclones as a function of the year of commercialization of upright and cylinder vacuum cleaners. An increasing trend is clearly observed, if not exponential. Before 2000, proposed models included one single cyclone. Between 2000 and 2010, their number regularly increased up to twelve, and single-cyclone

models quickly disappeared. Since 2010, no new model includes less than 10 cyclones and latest models even include more than 30 to 50 parallel cyclones.

The conclusion of the third strategy related to the number of cyclones is somehow validated in terms of relevance by these data. One should note also that the individual cyclones have been drastically miniaturized along the years, whereas the total volume of the device has been maintained or slightly reduced. Even if this criterion can hardly be quantified to check the third strategy, common trends are observed. As a conclusion, the performed intensification analysis seems fully coherent with industrial applications of this technology. One could even wonder if Dyson engineers did consciously apply process intensification strategies to propose innovative designs.

4. Integration of the case study in curriculum

As discussed by Rivas et al. (2020a, 2020b), the concepts of Process Intensification can be introduced in chemical engineering curriculum at various levels: the basic concepts can be presented in traditional engineering courses at undergraduate level (unit operations, transfer phenomena, process design, etc.), but advanced concepts may necessitate dedicated PI courses at graduate level. The successful integration of this case study (or adaptations of it) strongly depends on the student level, their skills and knowledge, as well as the expected outcomes. The following discussion will consider the basic case study without the extensions proposed in the previous section. Two scenarios are considered: (i) integration in a course dedicated to separation units at undergraduate level, and (ii) integration in a course dedicated to Process Intensification at graduate level. Table 3 summarizes and compares the two scenarios.

Table 3 : Comparison of two scenarios for integration of the case study in engineering curriculum.

Integration scenario	Cognitive Processes	Learning Outcomes	Format
Integration in a course dedicated to separation processes at undergraduate level	• Understand • Apply • Evaluate	• Describe the phenomena (properties and momentum, heat and mass transport) that influence a specific separation process, • Explain the impact of design variables and operating conditions on the performance of a separation unit, • Compare different separation processes, their operating conditions and performance, • Apply design rules, correlations and guidelines to estimate the performance of a separation process	• Tutorial • Home work • Team work
Integration in a course dedicated to Process Intensification at graduate level	• Understand • Apply • Analyze • Evaluate • Create	• Describe the physical and chemical phenomena that occur in a specific unit operation, • Explain the positive/negative impacts of design variables and operating conditions on the performance of a unit, • Compare the performances of different process units involving identical phenomena, according to various criteria, • Apply design rules, correlations and guidelines to estimate the performance of a process unit,	• Tutorial • Team work • Project-based learning

		• Identify degrees of freedom to improve the performance of a unit while satisfying design/operation constraints, • Propose intensification strategies to improve the multiple performance criteria of a process unit.	

Integration in a course dedicated to separation processes requires, as prerequisites, students to be familiar with cyclonic separations and evaluation methods of separation performance through collection efficiency and mechanical dissipated power. The concepts of Process Intensification (Quality, Efficiency and Sustainability) then appear natural for process improvement, and the action means (Time, Structure, Energy, Synergy) can be briefly introduced to contextualize the three strategies developed in the previous sections. This introduction to Process intensification can be performed as a short lecture or, more relevant, as an industrial conference. However, this overview of Process Intensification is not sufficient to let students propose the strategies by themselves. As a result, higher-order cognitive skills of the Bloom's taxonomy cannot be developed. Their understanding of the phenomena can be tested during application of the first strategy of the case study, in the analysis of the relation between flow rate and collection efficiency, and in the third strategy by parallelizing the units. The "Apply" and "Evaluate" cognitive processes are also put into practice during the development of each strategy and their final comparison. The case study can preferentially be used as a tutorial, but can also be a subject for home work: whatever the format, team work is beneficial, especially for the evaluation of the third strategy that require some astuteness or discussion. The learning outcomes, detailed in Table 3, therefore mainly focus on the skills and knowledge related to separation units, more than Process Intensification, since, in this

integration scenario, PI is mainly considered as a context for application of specific design strategies.

In the second scenario, the case study is used within a dedicated Process Intensification course. To reach higher-order cognitive processes, specific prerequisites should enable learners to “analyze” the original problem and “create” potential solutions by proposing intensification strategies by themselves. Prerequisites to the case study should therefore include at least (i) a precise definition of intensification criteria (Performance, Efficiency, Energy, Quality, Waste, etc.), (ii) a diversified view of intensification strategies and degrees of freedom in Process Design (Time, Scale, Energy, Synergy) and (iii) a large overview of Process Intensification technologies applying these strategies as inspirational sources. These three aspects should be presented as lectures and/or conferences, to cover a wide spectrum of applications and strategies, and could be complemented by simple direct-application tutorials before testing the case study. Rivas et al. (2020a, 2020b) provide numerous resources to organize this preliminary knowledge.

The learning outcomes, expected from the use of the case study, are therefore much more specific to Process Intensification: the proposal of intensification strategies, according to various degrees of freedom, within specific constraints, can be put into practice. This skill is, for sure, the hardest aspect of the missions of a chemical engineer, and calls for the creativity of the learners and their capacity to build transverse connections. For that reason, team work and project-based learning are the preferential formats to apply the case study: an open discussion, a divergent-thinking session or a short brainstorming is very beneficial for the group to analyze the degrees of freedom and propose strategies, before their quantitative evaluation and final comparison.

The pedagogic success of the case study can be assessed a posteriori by proposing similar problems to students and asking them for intensification strategies. Indeed, in this case study, all strategies emerge from the analysis of equations (1) to (6) that relate the performance criteria (collection efficiency and dissipated power) to design parameters and operating conditions: any system/process/unit whose efficiency can be mathematically related to design parameters and operating conditions, could be used as a case study to test the creativity of learners and their capacity to propose intensification strategies. The main difficulty lies in the complexity of these relations: whereas the present case study is governed by simple equations, many systems are described by complex sets of equations that hardly enable a direct analysis. Appropriate systems include isothermal tubular/mixed reactors with first-order or second-order reactions, isoperibolic heat-exchanger reactors with first-order reactions, membrane reactors with first-order reactions, gas-liquid and liquid-liquid contactors, etc.

5. Conclusions

The development of pedagogic problems for teaching process intensification can be a hard task especially when time constraints have to be taken into account. This work presented a case study dedicated to the sustainable intensification of a gas/solid separation unit, intending to improve three performance criteria: the collection efficiency, the process volume and the total dissipated power. Based on a reference cyclone and operating conditions, three strategies have been explored to understand the relative influences of various parameters and to design a new process capable of satisfying all objectives simultaneously. A combination of miniaturization and parallelization enabled to increase the collection efficiency while reducing the device volume and required power. Several directions are proposed to build new problems or extensions adapted to different teaching contexts or formats. Additional extensions could be proposed for other separation units whose efficiency and performance

criteria are well known and can be easily correlated as a function of geometric parameters and operating conditions. Scenarios for integration of the case study in various engineering curricula have been proposed, by differentiating the prerequisites and learning outcomes as a function of the student level and course objectives.

6. Nomenclature

a	Height of the gas inlet [m]
b	Width of the gas inlet [m]
B	Geometric parameter of the Stairmand cyclone [m]
C	Slip correction factor
D	Diameter [m]
D_e	Geometric parameter of the Stairmand cyclone [m]
h	Geometric parameter of the Stairmand cyclone [m]
H	Geometric parameter of the Stairmand cyclone [m]
ΔP	Pressure drop [Pa]
N_t	Number of gas revolutions in the cyclone
P	Power [W]
Q	Volume flow rate [m^3/s]
S	Geometric parameter of the Stairmand cyclone [m]
U	Velocity [m/s]
V	Volume [m^3]

Greek letters

α	Scale factor

η Efficiency

μ_g Dynamic viscosity of the gas [Pa·s]

ρ_p Particle density [kg/m^3]

τ Space time [s]

Subscripts

in Inlet

p Particle

p,50 Particle diameter corresponding to 50% collection efficiency

ref Relative to reference design

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8. Appendix

8.1. Development of the performance criteria of the third strategy

The third strategy requires expressing the total volume, the cutoff diameter and the total dissipated power as a function of the scale factor α and the number of parallel cyclones, N, while paying attention to the extensive or intensive nature of intermediate variables.

The total volume V_{tot} is the sum of all volumes of the individual cyclones. Since each cyclone is a small copy of the reference design, its volume V is:

$$V = \alpha^3 V_{ref}$$

The total volume, normalized by the reference is therefore:

$$\frac{V_{tot}}{V_{ref}} = N\alpha^3$$

Since the cutoff diameter is an intensive feature, the analysis can be performed for on single cyclone. Similarly to the development used for application of the second strategy, the normalized cutoff diameter is:

$$\frac{D_{p,50}}{D_{p,50,\mathrm{ref}}} = \sqrt{\frac{b}{b_{ref}}\frac{U_{in,ref}}{U_{in}}\frac{N_{t,ref}}{N_t}}$$

Whereas the ratio of geometric parameters b and b_{ref} only depends on the scale factor α, the division of the total flow rate through the N parallel cyclones also affects the ratios of the inlet velocity and number of revolutions:

$$\frac{U_{in,ref}}{U_{in}} = \left(\frac{Q_{ref}}{a_{ref}b_{ref}}\right)\left(\frac{Nab}{Q_{ref}}\right) = N\alpha^2$$

$$\frac{N_{t,ref}}{N_t} = \left(\frac{\tau_{ref}U_{in,ref}}{\pi D_{ref}}\right)\left(\frac{\pi D}{\tau U_{in}}\right) = \frac{V_{ref}}{V}.\frac{U_{in,ref}}{U_{in}}.\frac{Q}{Q_{ref}}.\frac{D}{D_{ref}} = \frac{1}{\alpha^3}.N\alpha^2.\frac{1}{N}.\alpha = 1$$

As a result, the ratio of cutoff diameter becomes:

$$\frac{D_{p,50}}{D_{p,50,\mathrm{ref}}} = \sqrt{\frac{b}{b_{ref}}.\frac{U_{in,ref}}{U_{in}}.\frac{N_{t,ref}}{N_t}} = \sqrt{\alpha.N\alpha^2.1} = \sqrt{N\alpha^3}$$

The total dissipated power can be decomposed in a similar way:

$$\frac{P_{tot}}{P_{ref}} = \frac{Q_{ref}\Delta P}{Q_{ref}\Delta P_{ref}} = \frac{D}{D_{ref}}.\frac{(a+b)}{(a_{ref}+b_{ref})}.\frac{a_{ref}b_{ref}}{ab}.\frac{U_{in}^2}{U_{in,ref}^2}.\frac{N_t}{N_{t,ref}}$$

$$= \alpha.\alpha.\left(\frac{1}{N\alpha^2}\right)^2.1.\frac{1}{\alpha^2} = \frac{1}{N^2\alpha^4}$$

8.2. Criteria maps for the third strategy

Figure 8, Figure 9 and Figure 10 respectively present the isovalue curves of the volume ratio V_{tot}/V_{ref} , the cutoff diameter ratio $D_{p,50}/D_{p,50,ref}$ and the power ratio P_{tot}/P_{ref} as a function of the scale factor α and the number of parallel cyclones N.

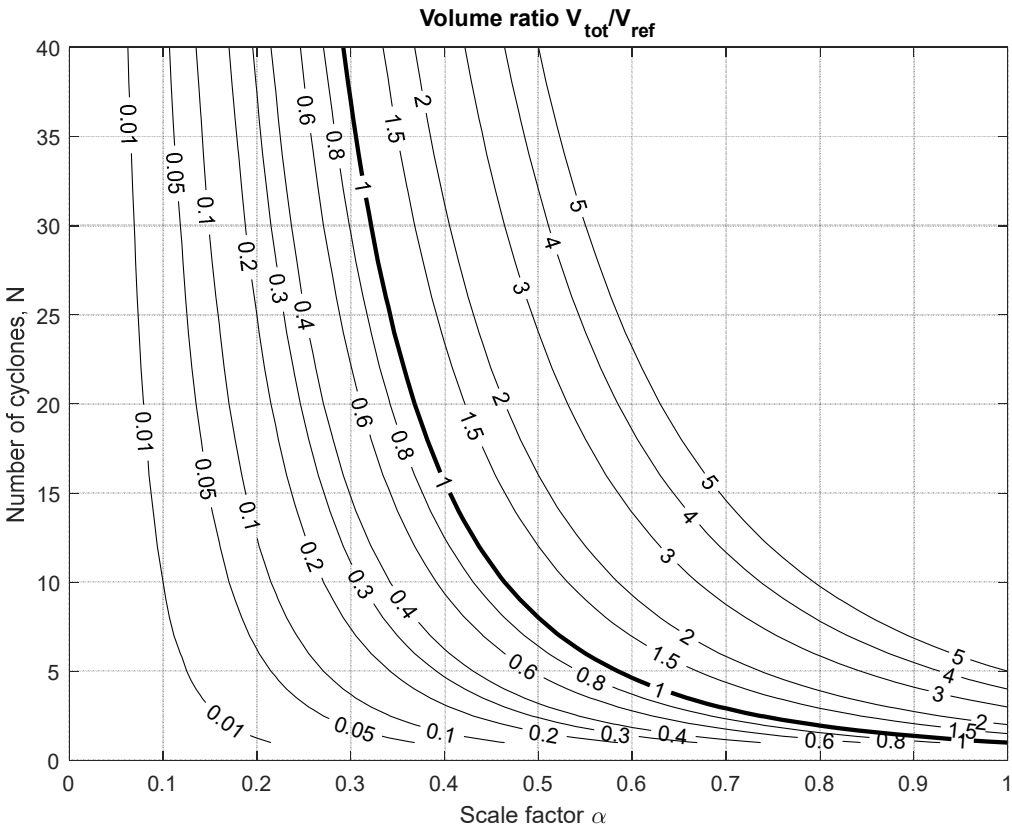


Figure 8 : Isovalue curves of the volume ratio V_{tot}/V_{ref} as a function of the scale factor α and the number of parallel cyclones N.

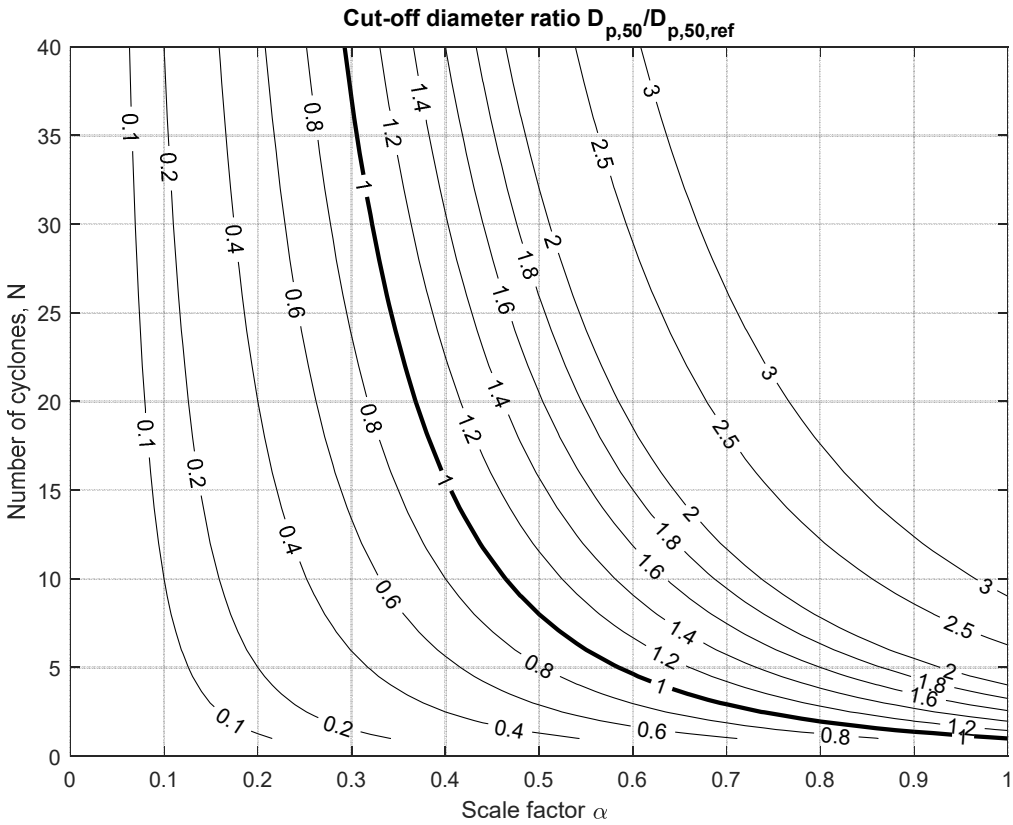


Figure 9 : Isovalue curves of the cut-off diameter ratio $D_{p,50}/D_{p,50,ref}$ as a function of the scale factor α and the number of parallel cyclones N.

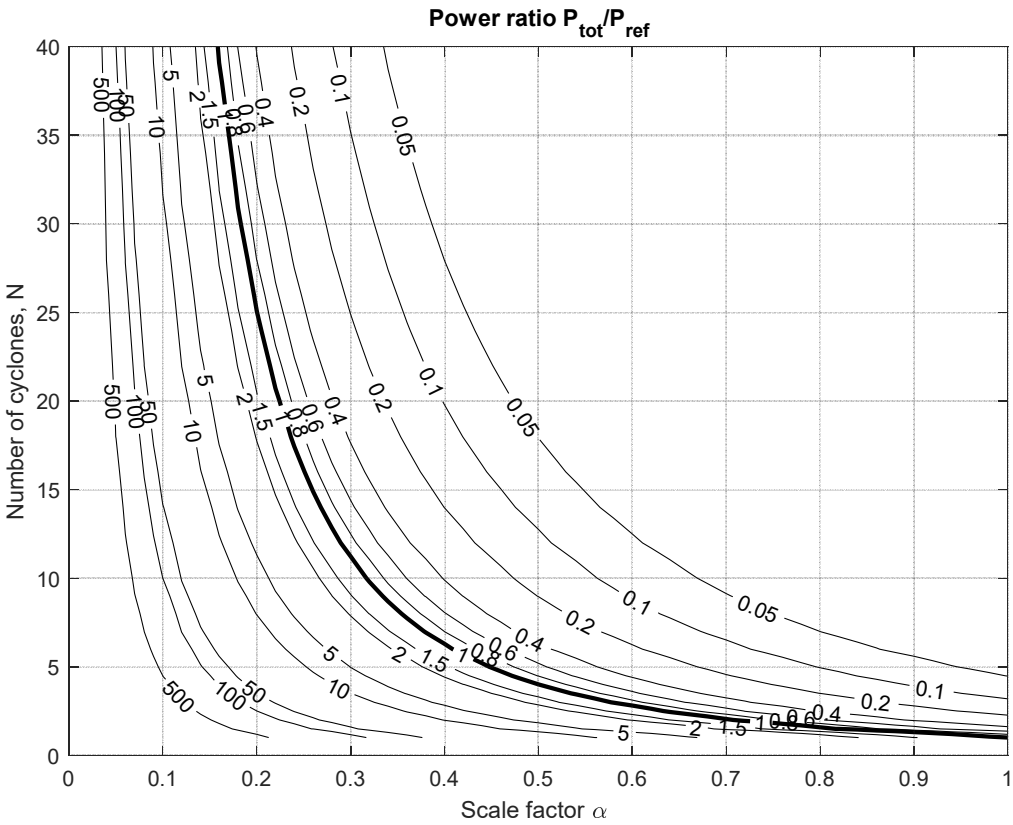
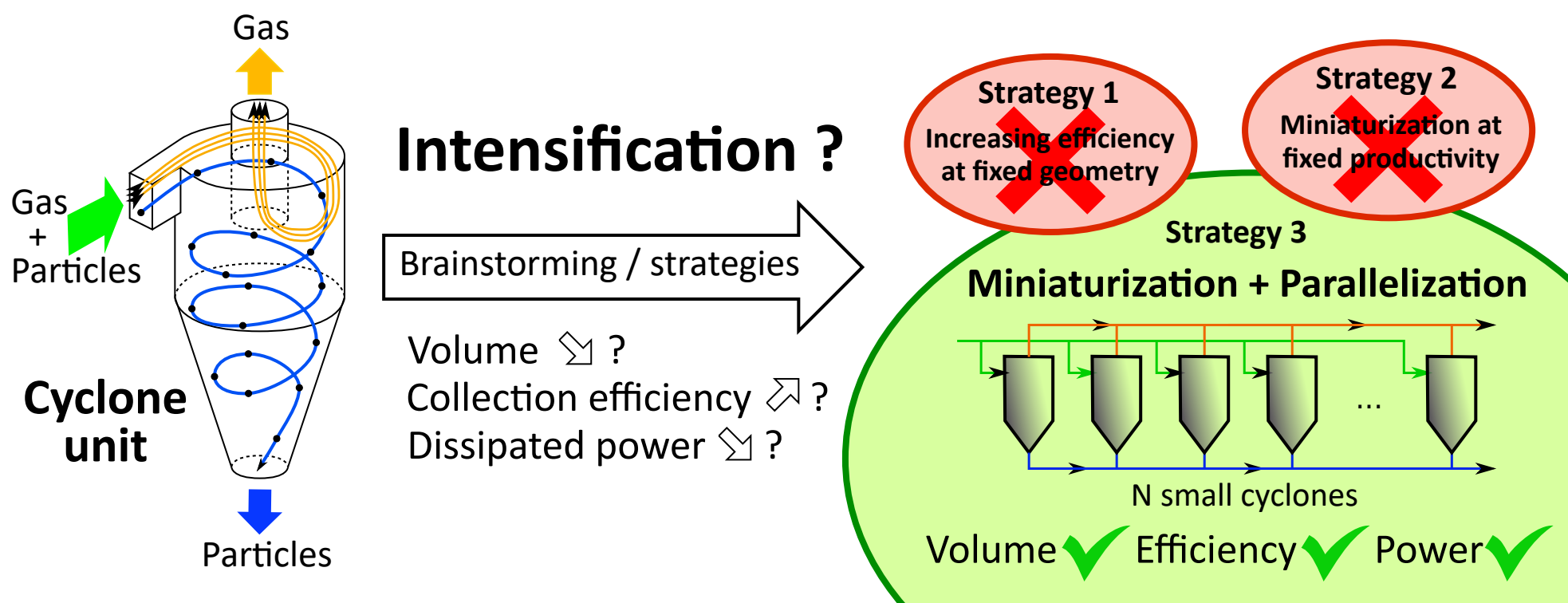


Figure 10 : Isovalue curves of the power ratio P_{tot}/P_{ref} as a function of the scale factor α and the number of parallel cyclones N.


Gas
Gas
+
Particles
Cyclone
unit
Particles
Intensification ?
Brainstorming / strategies
Volume ↘ ?
Collection efficiency ↗ ?
Dissipated power ↘ ?
Strategy 1
Increasing efficiency
at fixed geometry
Strategy 2
Miniaturization at
fixed productivity
Strategy 3
Miniaturization + Parallelization
...
N small cyclones
Volume
Efficiency
Power