

Industrial Usefulness and Technology Selection in Process Intensification: Energy-Normalized Metrics for Hydrodynamic Cavitation

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Abstract

Many process-intensification technologies show strong laboratory activity but fail to create industrial value after energy demand, chemical use, pressure drop, separation burden, fouling, maintenance, product quality, and reliability are included. A further source of failure is treating a technology family as a single interchangeable option, although different concepts, device classes, commercial designs, and operating envelopes may produce materially different physical and chemical effects. This paper proposes an energy-normalized, regime-based engineering framework for deciding when a specifically defined candidate technology or process module is industrially useful within a complete flowsheet.

The framework defines the Industrial Usefulness Window as the operating domain in which useful process benefit remains positive relative to a reference case after measurable penalties, uncertainty, and reliability constraints are included. It separates dimensional engineering performance indicators from normalized decision indices, including energy-normalized performance metrics and the Technology Net Benefit Index. The framework requires selection of the technology concept and design that best match the dominant process bottleneck, followed, where necessary, by process-specific adaptation of geometry, materials, operating conditions, and integration strategy.

Hydrodynamic cavitation is used as the main case study because it clearly distinguishes physical activity from industrial usefulness. Venturi, orifice, nozzle, vortex, passive shaped-flow-element, and rotary HC concepts differ in hydrodynamics, operating envelopes, and process effects. HC is most defensible when the selected device removes bottlenecks in micromixing, interfacial mass transfer, dispersion, oxidant utilization, controlled disruption, or pretreatment. It is weak when the limiting factor is thermodynamic equilibrium, refractory mineralization, unavoidable separation, product instability, material damage, or poor operability. The central conclusion is that HC should be selected and, when required, adapted as an integrated reaction–transport–separation intensification module, not adopted as a generic stand-alone treatment or conversion technology.

Keywords: process intensification; hydrodynamic cavitation; Industrial Usefulness Window; energy-normalized metrics; technology selection; process integration; scale-up

1. Introduction

Many process-intensification technologies show convincing laboratory activity but do not necessarily create industrial value. Higher conversion, faster removal, stronger mixing, improved heat or mass transfer, smaller droplets, or visible physical activity can demonstrate that a technology works locally, but not that it improves the complete process. Industrial usefulness requires a positive net effect after energy demand, chemical or consumable use, pressure drop, fouling, separation burden, maintenance, product quality, controllability, and reliability are considered.

This distinction is central to technology scale-up. A reactor may increase conversion while worsening selectivity or separation. A mixer may improve contact while producing stable emulsions. A heat exchanger may recover energy while adding pressure drop and fouling. A filtration system may improve solids removal while increasing cleaning frequency or product loss. Therefore, the relevant engineering question is not only whether a technology produces an effect, but whether it removes the dominant bottleneck with acceptable flowsheet-level consequences.

An additional scale-up error is to treat a technology name as if it described a single engineering object. Most technology families contain multiple concepts, configurations, geometries, energy-input routes, materials, and control strategies. These variants can address different rate-limiting phenomena and impose different penalties. Technology selection should therefore proceed from the relevant physical and chemical mechanisms and from the target process constraints, rather than from the generic technology label alone. The selected concept may also require process-specific adaptation before implementation, provided that the adaptation does not create new energy, separation, materials, or reliability penalties (Stankiewicz and Moulijn, 2000; Lutze et al., 2010, 2013; Ponce-Ortega et al., 2012).

Hydrodynamic cavitation is used in this paper as the principal case study because it clearly exposes the difference between physical activity and industrial usefulness. HC can generate turbulence, pressure pulses, shear, microjets, interfacial renewal, droplet or particle breakup, and, in selected aqueous systems, reactive short-lived species. These effects make HC attractive for wastewater treatment, oxidative or hybrid polishing, oxidative desulfurization, biodiesel and renewable-fuel processing, sludge and biomass pretreatment, heavy-oil conditioning, fuel homogenization, and multiphase contacting (Gogate and Pandit, 2000, 2001; Gagol et al., 2018; Mancuso et al., 2020; Panda et al., 2020; Oo et al., 2021; Somnuk et al., 2021; Sawarkar et al., 2019; Stebeleva et al., 2021; Zheng et al., 2022; Saylam, 2026a, 2026b, 2026c).

The industrial question, however, is not simply whether a device is described as a hydrodynamic cavitation reactor or whether cavitation can be generated under selected laboratory conditions. A nominal HC device may operate in regimes where cavitation is weak, intermittent, or absent, and observed process effects may arise partly or predominantly from turbulence, high shear, pressure fluctuations, and intense mixing. The relevant question is whether the selected HC concept, device configuration, verified hydrodynamic operating regime, and scale-up transferability improve the complete process after pumping power, pressure drop, oxidant or additive consumption, heat generation, erosion, fouling, phase separation, product quality, maintenance, controllability, and reliability are accounted for.

A laboratory result showing faster degradation, higher apparent conversion, stronger operating intensity, or smaller droplets is therefore insufficient unless the responsible mechanism is identified, the effect remains reproducible at the required scale, and the net benefit remains positive after downstream processing and other flowsheet-level consequences are included.

The objective of this paper is to develop an energy-normalized, regime-based framework for deciding when a specifically defined candidate technology or process module deserves industrial development. The framework evaluates useful benefit relative to a defined reference case and requires that the selected concept, design, and operating configuration remain beneficial after measurable penalties, uncertainty, reliability constraints, and process-integration requirements are included. Hydrodynamic cavitation is then used as a demanding case application of the framework.

2. Scope, novelty, and contribution

This paper is not a general review of hydrodynamic cavitation mechanisms, reactor designs, wastewater treatment, fuel upgrading, biodiesel production, or numerical modeling. These topics are already well covered in the literature. The scope here is narrower and more decision-oriented: to develop a practical engineering framework for judging when a candidate process-intensification technology is industrially useful within a complete flowsheet.

The framework is technology-neutral and is demonstrated through hydrodynamic cavitation. It evaluates not only whether a specifically defined technology or process module can create a positive net benefit, but also whether the selected concept or configuration is a defensible candidate after energy and chemical demand, separation burden, maintenance, product quality, scale-up transferability, reliability, uncertainty, and hard operating constraints are accounted for.

The main contribution is the Industrial Usefulness Window: an operating-domain concept that distinguishes useful technology integration from local activity. The paper also formalizes energy-normalized metrics and reference-based decision indices, including ENTM, ENTM*, TNBI, CNBI, separation-penalty ratio, and reliability ratio.

The novelty is not the claim that a candidate technology or process module can intensify a process. The novelty is the decision architecture for determining when a specifically selected and, where necessary, adapted concept, configuration, and operating regime provides transferable industrial value rather than only measurable laboratory activity. Hydrodynamic cavitation is used as the principal case application.

3. Hydrodynamic cavitation as the case technology

Hydrodynamic cavitation is used here as the principal case technology because it combines fluid dynamics, interfacial renewal, shear, turbulence, multiphase effects, and, in selected aqueous systems, radical-assisted chemistry. It is therefore a useful test case for distinguishing physical activity from industrial usefulness.

HC occurs when local liquid pressure falls below the vapor pressure, causing cavities to form, grow, and collapse during pressure recovery. Collapse events can generate pressure pulses, microjets, shear, turbulence, droplet or particle breakup, and renewed interfaces. These effects can intensify micromixing, mass transfer, dispersion, oxidant contact, disruption, and pretreatment.

The industrial value of HC depends on whether these effects remove a real bottleneck. In liquid-liquid systems, HC may improve interfacial area and phase contact. In gas-liquid systems, it may improve dispersion and mass transfer. In sludge, biomass, or cell-containing systems, it may support controlled disruption. In oil, fuel, and wastewater applications, it may improve contact, polishing, homogenization, or pretreatment. However, the same mechanisms may become counterproductive if they create excessive energy demand, erosion, fouling, stable emulsions, poor dewatering, product instability, or separation burden.

A device classified or described as a hydrodynamic cavitation reactor may operate under conditions in which cavitation is weak, intermittent, or not established. Under such conditions, observed process intensification may arise partly or predominantly from turbulence, high shear, hydrodynamic pressure fluctuations, and intense mixing rather than from cavity formation and collapse.

Figure 1 illustrates the generic pressure-recovery sequence in a constricted-flow hydrodynamic cavitation device. Flow acceleration through the restriction lowers the local static pressure; when the pressure falls sufficiently below the liquid vapor pressure, cavities may form and grow, then collapse during downstream pressure recovery. The resulting process effects may include pressure pulsations, shear, turbulence, interfacial renewal, and intense mixing. The figure is conceptual: cavity formation and collapse depend on device geometry, fluid properties, temperature, dissolved gas content, flow rate, and downstream pressure, and should be verified rather than assumed for every nominal HC device or operating condition.

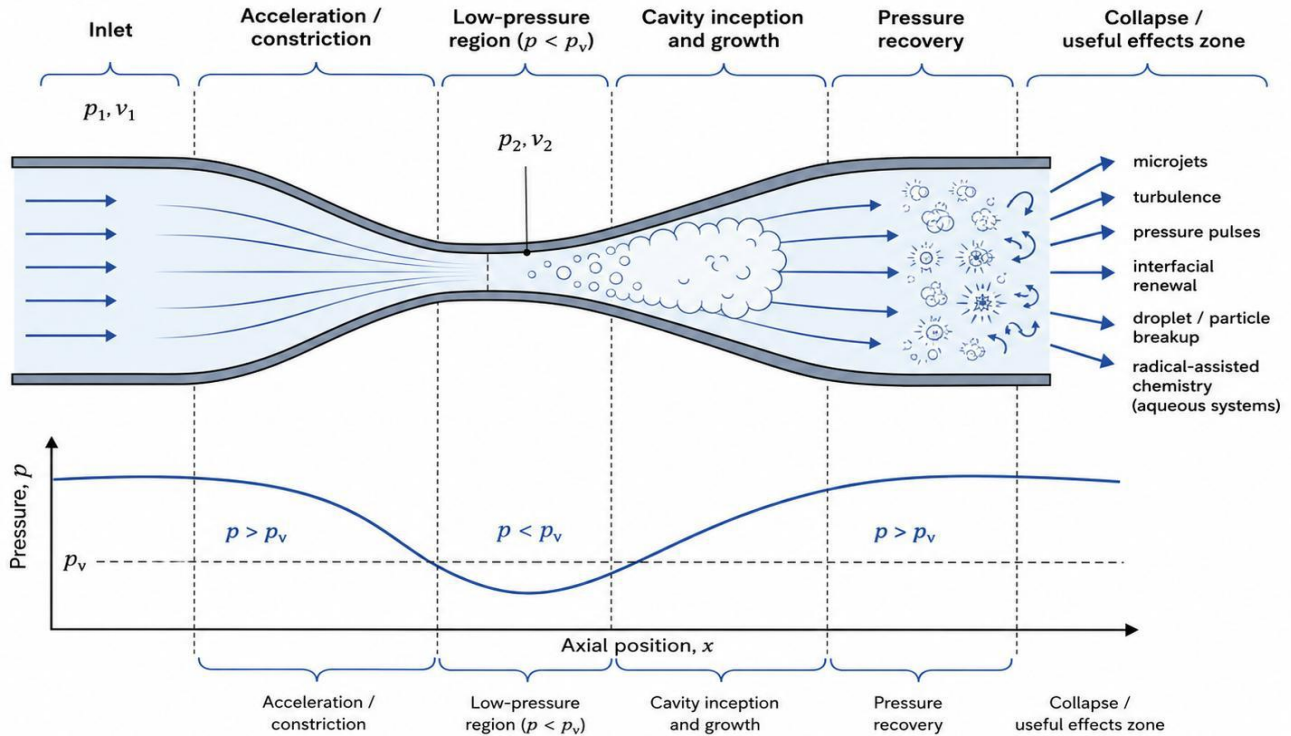


Figure 1. Conceptual pressure-recovery mechanism in a constricted-flow hydrodynamic cavitation device.

3.1 Cavitation generation, cavitation number, and device classes

HC devices generate cavitation by imposing pressure and velocity gradients on a liquid. Main device classes include Venturi tubes, orifice or multi-hole plates, nozzles, vortex reactors, passive shaped-flow elements, and rotary or rotor-stator generators. Within each class, commercial and custom designs can differ in geometry, pressure-recovery behavior, materials, adjustability, and control strategy. Figure 2 summarizes representative HC concepts; the illustration is conceptual, and the occurrence, location, and intensity of cavitation must be verified for the selected device and operating condition. Stationary devices are mechanically simple and attractive for inline integration, but they may suffer from pressure loss, clogging, limited adjustability, or erosion. Rotary devices offer adjustable intensity through speed and geometry, but introduce moving parts, sealing requirements, heat generation, and maintenance risks (Gogate and Pandit, 2000, 2001; Blagojević et al., 2023; Zheng et al., 2022).

A common nondimensional descriptor is the cavitation number:

$$\sigma = \frac{p_2 - p_v}{0.5\rho v^2}$$

Equation 1. Cavitation number, where p_2 is a representative recovery pressure, p_v is vapor pressure, ρ is density, and v is characteristic velocity.

Low σ generally indicates stronger cavitation, but industrial performance is not monotonic with decreasing σ . Too little cavitation produces weak intensification; excessive vapor generation can cushion collapse, waste energy, promote erosion, decompose oxidants, or create emulsions. Equal σ values do not guarantee equal performance because collapse location, residence pattern, wall interaction, and hydrodynamic field structure depend strongly on device geometry (Gogate and Pandit, 2000; Ranade, 2022).

Although hydrodynamic cavitation is the principal case technology in this paper, ultrasonic or acoustic cavitation is a useful comparator because it can generate related bubble-driven phenomena through a different energy-input route. In ultrasonic cavitation, alternating acoustic pressure waves drive bubble nucleation, oscillation, growth, and collapse; the resulting bubble dynamics can produce microstreaming, shear, interfacial renewal, localized high-temperature and high-pressure regions, and, in suitable liquid systems, reactive short-lived species (Suslick et al., 1999; Bhangu and Ashokkumar, 2016). These effects overlap mechanistically with hydrodynamic cavitation, where pressure and velocity gradients in flowing liquids generate cavities and collapse zones that can intensify micromixing, interfacial transfer, dispersion, and selected reactive processes (Gogate and Pandit, 2000, 2001; Gogate, 2008; Zheng et al., 2022). The engineering envelope is nevertheless different: ultrasonic cavitation is often valuable for small-volume screening, mechanistic studies, and laboratory proof-of-effect, whereas hydrodynamic cavitation is generally more compatible with continuous inline processing and high-throughput industrial integration (Gogate and Pandit, 2005; Cako et al., 2022; Zheng et al., 2022). Therefore, positive ultrasonic results should not be transferred directly to hydrodynamic systems without energy-normalized comparison under matched temperature, pressure, composition, residence time, separation, and reliability constraints.

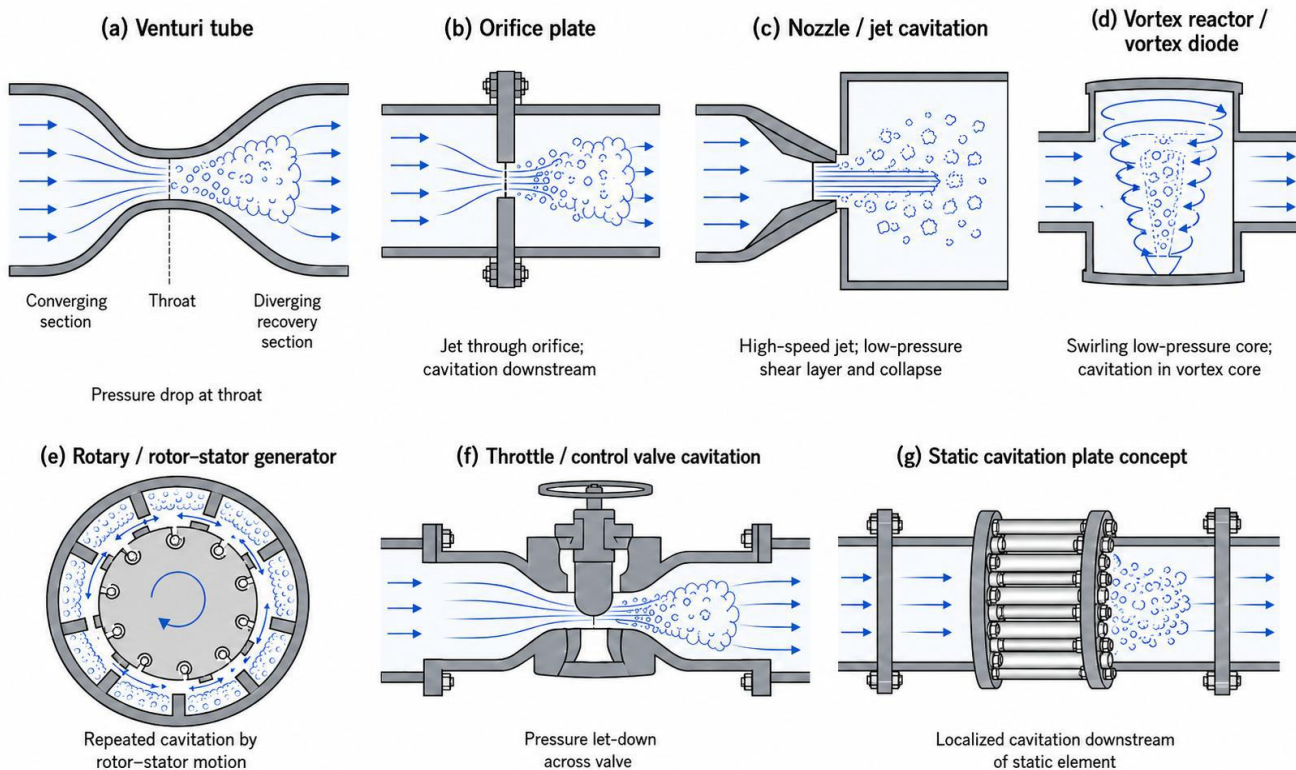


Figure 2. Representative hydrodynamic cavitation device classes and their principal cavitation-generation mechanisms.

Hence, hydrodynamic cavitation is not a single device concept. Different reactor classes generate local pressure reduction, flow acceleration, shear, turbulence, and pressure recovery through different geometries and hydrodynamic fields. These device classes are not interchangeable. Their usefulness depends on how the generated hydrodynamic regime matches the dominant process bottleneck and on the associated pressure drop, erosion, fouling, separation behavior, controllability, maintenance demand, and scale-up transferability. Table 1 therefore compares the principal physical basis, best-use window, and main limitations of representative HC concepts.

Table 1. Device-concept dependence of hydrodynamic cavitation usefulness.

| HC concept | Physical basis | Best-use window | Main limitation or risk |
|-----------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Venturi tube | Converging throat lowers static pressure; diffuser recovers pressure and promotes collapse/mixing. | Inline contacting, oxidant transfer, liquid-liquid ODS, moderate AOP intensification. | Fixed geometry, pressure-drop cost, sensitivity to feed properties, recovery-zone erosion. |
| Orifice or multi-hole plate | Sudden contraction creates high-velocity jets and downstream collapse zones. | Low-cost screening, wastewater contacting, simple emulsification, retrofit when solids are manageable. | High pressure loss, clogging, non-uniform distribution, erosion, scale-up sensitivity. |
| Nozzle or jet cavitation | High-velocity jet creates localized cavitating shear or impingement zones. | Reactive injection, reagent contacting, localized mixing, gas-liquid entrainment. | Localized treatment volume, impingement erosion, scale-up depends on jet penetration. |
| Vortex reactor | Swirling flow forms a low-pressure core with more distributed cavitation. | Continuous water treatment where reduced wall impact or controlled residence pattern is useful. | Hydraulic design complexity; sensitivity to viscosity, gas fraction, solids, and flow regime. |
| Rotary or rotor-stator generator | Moving elements generate repeated pressure fluctuations and shear zones. | Sludge or cell disruption, biomass pretreatment, strong dispersion, adjustable conditioning. | Moving parts, seals, bearings, heat generation, fatigue, direct power measurement required. |
| Passive shaped-flow element | A passive shaped-flow element, such as a stationary cavitation plate or fixed profiled insert, creates local flow acceleration and pressure reduction, followed by deceleration and pressure recovery. | Compact inline contacting, fuel homogenization, oxidant-assisted polishing, and retrofit duties where a fixed-geometry, no-moving-parts device is advantageous. | Performance depends strongly on element geometry, flow rate, pressure drop, feed properties, fouling, and erosion; the operating window may require process-specific adaptation. |
| Ultrasonic or acoustic cavitation | Alternating acoustic pressure waves generated by a transducer produce bubble nucleation, oscillation, collapse, microstreaming, shear, and localized interfacial renewal. | Laboratory screening, small-volume mechanistic studies, sonochemical activation, emulsification, dispersion, and flow-through sonoreactors where acoustic energy distribution can be controlled. | Acoustic attenuation, non-uniform energy fields, limited scale-up transferability, transducer efficiency, heat management, sonotrode wear, fouling, and high specific energy demand at larger scale. |

The design question is not which device generates the strongest cavitation, but which device concept and configuration produce the required mechanism with acceptable pressure drop, erosion, fouling, separation

compatibility, scale-up transferability, controllability, maintenance demand, and reliability. Device class is therefore only the first selection layer: materially different versions within the same class should be compared as separate candidates, and a promising commercial or custom design may require application-specific adjustment of geometry, materials, operating range, or control strategy before implementation (Gogate and Pandit, 2000, 2001; Ranade, 2022; Zheng et al., 2022).

3.2 Functional mechanisms and useful effects

The useful effects of HC can be grouped into five engineering mechanisms, as shown in Table 2: micromixing, interfacial renewal, radical-assisted oxidation, disruption, and structure or viscosity modification. Micromixing reduces concentration gradients and improves reagent, catalyst, oxidant, or extractant distribution. Interfacial renewal improves gas-liquid or liquid-liquid contact. Radical-assisted oxidation may support degradation or polishing in aqueous oxidant-containing systems, but remains strongly matrix-dependent (Saylam, 2026b). Disruption is useful when cells, flocs, particles, agglomerates, or biomass structures limit downstream conversion or extraction. Structure or viscosity modification can be relevant for heavy oils, fuels, and blending, but only if the benefit is retained after storage and handling.

Table 2. Functional mechanisms governing HC performance and reporting.

| Mechanism | Physical origin | When useful | Penalty if overused | Best reporting metric |
|-------------------------------------|-----------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| Micromixing and turbulence | Velocity gradients, vortices, pressure pulses, rapid reactant redistribution. | Local concentration gradients or poor reagent distribution limit rate or quality. | Energy and heat without additional kinetic benefit; noise and vibration. | Rate or quality gain per kWh; residence-time reduction per kWh. |
| Interfacial renewal and dispersion | Bubble and droplet generation, interface breakup, surface renewal. | Gas-liquid or liquid-liquid transfer limits reaction, extraction, oxidation, or blending. | Stable emulsions, longer settling, demulsifier demand, product or solvent loss. | $k_L a$, droplet size, oxidant utilization, separation time per kWh. |
| Radical-assisted oxidation | Localized collapse and oxidant activation in aqueous or oxidant-assisted systems. | Partial oxidation improves biodegradability, color, odor, toxicity, or polishing. | Oxidant waste, radical scavenging, by-products, incomplete mineralization. | kg COD, TOC, or target pollutant removed per kWh and per kg oxidant. |
| Disruption and disintegration | Microjets, shear, repeated collapse, particle/floc/cell breakup. | Physical structure limits extraction, digestion, disinfection, or biodegradability. | Fines, poor dewatering, filtration losses, fouling, soluble refractory organics. | Net downstream yield or energy gain; dewatering/fouling index. |
| Structure or viscosity modification | Shear, structural breakdown, dispersion, homogenization. | Pumpability, heat transfer, blending, additive distribution, or contact is limiting. | Viscosity rebound, asphaltene instability, sediment, wear, separation difficulty. | Retained viscosity, homogenization, or blending benefit per kWh after storage. |

A condition that improves mass transfer or disruption may still be industrially weak if it worsens separation, dewatering, fouling, product quality, maintenance, or energy consumption. HC performance

should therefore be reported in mechanism-relevant engineering units, not only as removal percentage, conversion, or visible cavitation activity.

3.3 Minimum effective cavitation intensity

A common development error is to assume that stronger cavitation is always better. In industrial design, the preferred operating point is the minimum effective cavitation intensity that reproducibly removes the dominant bottleneck. Below this level, cavitation is too weak to generate useful intensification. Above the minimum effective intensity, additional severity may increase flowsheet-level penalties faster than it increases useful output. The term flowsheet-level penalties refers collectively to the additional burdens that may accompany a candidate intensification technology, including energy demand, chemical or consumable use, pressure drop, downstream separation difficulty, fouling, maintenance exposure, product-quality loss, controllability limits, and reliability risk.

This trade-off defines a practical operating window rather than a single optimum based only on cavitation strength. Figure 3 illustrates this concept schematically. At low severity, the useful process effect is insufficient. At excessive severity, energy demand, separation burden, erosion, fouling, product instability, or reliability penalties may dominate. Between these limits, HC can be industrially useful when the selected device and operating condition provide enough intensification without creating larger downstream or operability burdens.

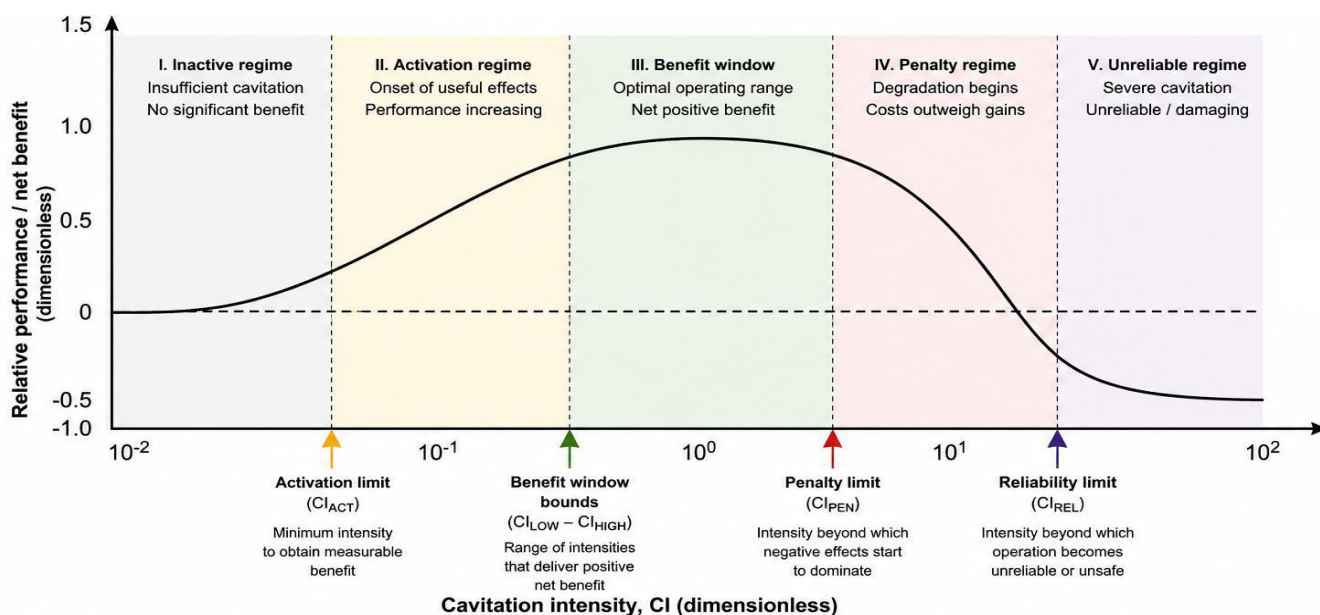


Figure 3. Industrial Usefulness Window. HC should be optimized inside the region where useful process effects exceed energy, separation, and reliability penalties. The x-axis represents a conceptual cavitation-intensity descriptor, CI, which may include cavitation number, pressure drop, power density, rotor speed, residence time, number of passes, or pressure-fluctuation intensity depending on the device and application. The figure is conceptual; boundaries must be determined experimentally for each feed, device, and application.

The practical conclusion is that HC should not be optimized for maximum cavitation intensity. It should be operated inside the usefulness window where the useful process benefit remains positive after the relevant flowsheet-level penalties and hard constraints are included. The same principle applies to other technologies: mixers should not be optimized only for maximum shear, heat exchangers only for maximum heat flux, and filtration systems only for maximum initial flux.

4. Metrics and decision architecture

Industrial evaluation of a candidate technology or process module requires more than reporting removal percentage, conversion, yield, heat-transfer improvement, filtration efficiency, droplet-size reduction, or qualitative operating intensity. Such indicators may demonstrate local activity, but they do not establish industrial usefulness. A generic technology label is also too broad for a defensible comparison because different concepts, configurations, commercial designs, and process-specific adaptations may produce materially different physical and chemical effects.

In this paper, a candidate technology or process module is a bounded process implementation intended to perform a defined flowsheet function. It may comprise an individual device, a reactor, a unit operation, a conversion or reforming sub-process, an integrated hybrid system, or another process-intensification module, together with the auxiliary operations required for its intended function. The candidate is denoted as (Q). Alternative concepts, designs, or adapted versions are treated as separate candidates (Q_i), rather than as interchangeable examples of the same technology class.

Each candidate should be evaluated relative to a defined reference case that performs the same functional duty and should be assessed within the same process boundary. The comparison should include delivered energy, chemical or consumable use, pressure drop, separation burden, maintenance exposure, product quality, reliability, uncertainty, and hard operating constraints. The reference case may be the current process, a conventional design, or another technically credible alternative, but its function, boundary, feed basis, and useful-output definition must remain consistent throughout the comparison. Hydrodynamic cavitation is treated as the principal case, where ($Q = HC_i$) for a specifically defined HC device and operating configuration.

4.1 Energy-normalized performance metrics

For a selected useful output Y , the dimensional Energy-Normalized Treatment/Conversion Metric is defined as:

$$\text{ENTM}_{Y,Q} = \frac{\Delta Y_{\text{useful},Q}}{E_{\text{total},Q}}$$

Equation 2. Dimensional energy-normalized performance metric for candidate technology Q , where $\Delta Y_{\text{useful},Q}$ is the useful output achieved by the technology and $E_{\text{total},Q}$ is the total delivered energy on the same process boundary.

The useful output must correspond to the real industrial objective. It may represent COD removed, sulfur removed from final fuel, on-spec product yield, heat recovered, solids captured, filtrate-quality improvement, or retained viscosity benefit. The energy term should include the directly required hydraulic, electrical, thermal, recirculation, pumping, mixing, cooling, compression, or backwash energy.

For hydrodynamic cavitation:

$$\text{ENTM}_{Y,HC} = \frac{\Delta Y_{\text{useful},HC}}{E_{\text{total},HC}}$$

Equation 3. Hydrodynamic-cavitation-specific energy-normalized performance metric.

A useful literature example is provided by Gostiša et al. (2021), who investigated COD reduction using a pinned-disc rotating hydrodynamic cavitation generator. In the best reported configuration, COD was

reduced by 31% after 15 liquid passes, with a reported specific energy consumption of about 8.2 kWh kg⁻¹ COD removed. Expressed in the reciprocal ENTM form, this corresponds to:

$$\text{ENTM}_{\text{COD,HC}} = \frac{1}{8.2} = 0.122 \text{ kg COD kWh}^{-1}$$

Equation 4. Energy-normalized COD removal for the reported rotating hydrodynamic cavitation case.

This example shows why percentage removal alone is insufficient. A 31% COD reduction may be attractive or unattractive depending on energy demand, wastewater matrix, downstream treatment, separation behavior, fouling, and reliability (Saylam, 2026a; Saylam, 2026b).

For comparison with a reference case, the dimensionless normalized metric is:

$$\text{ENTM}_{Y,Q/\text{ref}}^* = \frac{\text{ENTM}_{Y,Q}}{\text{ENTM}_{Y,\text{ref}}}$$

Equation 5. Dimensionless normalized energy metric, where $\text{ENTM}_{Y,Q}$ is the energy-normalized performance of the candidate technology and $\text{ENTM}_{Y,\text{ref}}$ is the corresponding value for the reference case.

A value of $\text{ENTM}_{Y,Q/\text{ref}}^* > 1$ indicates higher useful output per unit energy than the reference. A value below one indicates that the technology may be active but not energy-competitive under the selected boundary.

4.2 Net-benefit and penalty architecture

Energy-normalized metrics are necessary but not sufficient. A technology may improve useful output per kWh while increasing chemical demand, separation burden, fouling, maintenance, product-quality loss, or reliability risk. Therefore, a Technology Net Benefit Index (TNBI) is introduced:

$$\text{TNBI}_{\text{ref},Q} = \frac{B_{\text{ref},Q} R_{\text{rel},Q}}{P_{\text{ref},Q}}$$

Equation 6. Technology Net Benefit Index for candidate technology Q , where $B_{\text{ref},Q}$ is the useful-benefit ratio, $R_{\text{rel},Q}$ is the reliability ratio, and $P_{\text{ref},Q}$ is the combined penalty factor.

For hydrodynamic cavitation:

$$\text{CNBI}_{\text{ref}} = \text{TNBI}_{\text{ref,HC}}$$

Equation 7. Cavitation Net Benefit Index as the hydrodynamic-cavitation-specific form of the Technology Net Benefit Index.

The useful-benefit ratio is:

$$B_{\text{ref},Q} = \frac{Y_Q}{Y_{\text{ref}}}$$

Equation 8. Useful-benefit ratio, where Y_Q and Y_{ref} are beneficial outputs expressed on the same process boundary and with the same “larger-is-better” convention for the candidate technology and reference case, respectively.

The principal penalty ratios are:

$$\Pi_{E,Q} = \frac{E_Q}{E_{\text{ref}}}$$

Equation 9. Energy penalty ratio.

$$\Pi_{\text{chem},Q} = \frac{C_{\text{chem},Q}}{C_{\text{chem,ref}}}$$

Equation 10. Chemical or consumable penalty ratio.

$$\Psi_{\text{sep},Q} = \frac{S_{\text{sep},Q}}{S_{\text{sep,ref}}}$$

Equation 11. Separation penalty ratio.

$$\Psi_{\text{maint},Q} = \frac{M_Q}{M_{\text{ref}}}$$

Equation 12. Maintenance penalty ratio.

$$\Psi_{\text{qual},Q} = \frac{PQ_{\text{loss},Q}}{PQ_{\text{loss,ref}}}$$

Equation 13. Product-quality or downstream-compatibility penalty ratio.

Neutral terms are set equal to one. If a denominator is zero, the burden should be expressed through a total cost, resource, or flowsheet-burden ratio rather than forced into an undefined direct ratio.

Reliability is expressed through availability:

$$A_Q = \frac{t_{\text{stable},Q}}{t_{\text{planned},Q}}$$

Equation 14. Availability of the candidate technology in real operation.

$$A_{\text{ref}} = \frac{t_{\text{stable,ref}}}{t_{\text{planned,ref}}}$$

Equation 15. Availability of the reference case.

$$R_{\text{rel},Q} = \frac{A_Q}{A_{\text{ref}}}$$

Equation 16. Reliability ratio.

The combined penalty factor may be calculated as an unweighted geometric mean:

$$P_{\text{ref},Q} = (\Pi_{E,Q} \Pi_{\text{chem},Q} \Psi_{\text{sep},Q} \Psi_{\text{maint},Q} \Psi_{\text{qual},Q})^{1/m}$$

Equation 17. Combined penalty factor, where m is the number of included penalty categories.

The geometric mean avoids arbitrary weighting, but it should not hide critical failure modes. Therefore, hard constraints must also be declared:

$$G_{j,Q} \leq G_{j,\text{max}}$$

Equation 18. Hard constraint for candidate technology Q , where $G_{j,Q}$ may represent a critical limit such as maximum allowable pressure drop, erosion rate, fouling rate, product-quality loss, residual oxidant, emulsion stability, corrosion rate, vibration, temperature rise, downtime, or safety margin.

If any hard constraint is violated, the candidate technology should be rejected or redesigned even if the averaged penalty factor and TNBI appear favorable.

A compact HC calculation illustrates the index. If an HC wastewater condition gives $B_{\text{ref},HC} = 1.55$, $R_{\text{rel},HC} = 0.95$, and $P_{\text{ref},HC} = 1.03$, then:

$$\text{CNBI}_{\text{ref}} = \frac{1.55 \times 0.95}{1.03} = 1.43$$

Equation 19. Example Cavitation Net Benefit Index for wastewater polishing.

This value indicates positive net benefit relative to the selected reference, but not universal superiority. The HC condition remains attractive only under the stated feed, process boundary, energy basis, separation behavior, reliability, and quality constraints.

4.3 Industrial Usefulness Window

The Industrial Usefulness Window is the operating domain where a specific candidate technology configuration gives a positive net contribution relative to a reference case while remaining inside critical process constraints. A technology family may therefore contain multiple, non-identical usefulness windows. For a candidate technology Q , the operating condition may be represented as:

$$x_Q = (\Delta p, w, T_{\text{op}}, t_{\text{res}}, N_{\text{pass}}, D_c, C_{\text{add}}, \phi, P_{\text{feed}}, Z_{\text{control}})$$

Equation 20. Process-condition vector for candidate technology Q , where the terms represent pressure drop Δp , flow rate w , operating temperature T_{op} , residence time t_{res} , number of passes N_{pass} , device configuration D_c , additive dose C_{add} , phase ratio ϕ , feed properties P_{feed} , and control variables Z_{control} .

A technology-severity descriptor is defined as:

$$SQ = SI_Q(x_Q)$$

Equation 21. Technology-severity descriptor generated by the operating condition.

For HC, SI_Q may represent cavitation number, pressure drop, power density, rotor speed, residence time, number of passes, or pressure-fluctuation intensity. For other technologies, it may represent mixing power, heat flux, transmembrane pressure, filtration flux, residence time, catalyst loading, or separator loading. Severity alone does not prove usefulness; it must be linked to net process benefit.

The Industrial Usefulness Window is defined as:

$$\Omega_{\text{IUW},Q} = \{x_Q: B_{\text{ref},Q}(x_Q) > 1, \text{TNBI}_{\text{ref},Q}(x_Q) > 1, G_{j,Q}(x_Q) \leq G_{j,\text{max}}\}$$

Equation 22. Industrial Usefulness Window for candidate technology Q .

For hydrodynamic cavitation:

$$\Omega_{\text{IUW},HC} = \{x_{HC}: B_{\text{ref},HC}(x_{HC}) > 1, \text{CNBI}_{\text{ref}}(x_{HC}) > 1, G_{j,HC}(x_{HC}) \leq G_{j,\text{max}}\}$$

Equation 23. Hydrodynamic-cavitation-specific Industrial Usefulness Window.

A stricter practical form includes uncertainty:

$$\Omega_{IUW,Q} = \{x_Q: B_{\text{ref},Q}(x_Q) - 1 > U_B(x_Q), \text{TNBI}_{\text{ref},Q}(x_Q) - 1 > U_{\text{TNBI}}(x_Q), G_{j,Q}(x_Q) \leq G_{j,\text{max}}\}$$

Equation 24. Practical Industrial Usefulness Window including uncertainty and hard constraints.

The practical implication is simple: a weak condition remains outside the window because it gives little useful effect; an excessive condition may also fall outside because penalties dominate; a moderate condition may be industrially useful if it removes the bottleneck without excessive burden. The window is configuration-specific, so a useful operating point for one design should not be transferred automatically to another. For HC, this means optimizing the selected device for the minimum effective cavitation severity, not maximum cavitation intensity.

5. Decision-support visualizations for hydrodynamic cavitation screening

The metric framework provides quantitative tools for evaluating industrial usefulness, but early-stage screening also benefits from compact visual interpretation. For HC, two visualization tools are useful: a Decision Landscape and a Regime Radar. These figures are not substitutes for ENTM, ENTM*, TNBI, CNBI, separation-penalty, or reliability calculations; their role is to identify where HC is likely promising, conditional, or weak before detailed pilot data are available.

The visualizations in this section are semi-quantitative screening aids. They are intended for early triage and communication, not as universal HC performance maps or substitutes for measured ENTM, ENTM*, TNBI, CNBI, separation-penalty, and reliability calculations. The scores should be interpreted as illustrative expert-screening values unless recalibrated with measured data for a defined feed, device, operating condition, reference process, and flowsheet boundary. Higher usefulness scores indicate stronger expected bottleneck removal with retained flowsheet benefit, while higher penalty-pressure scores indicate greater expected energy, separation, product-quality, maintenance, materials, or operability burden. Bubble size represents evidence maturity or scale-up confidence.

5.1 Hydrodynamic-cavitation Decision Landscape

The Hydrodynamic-Cavitation Decision Landscape, presented in Figure 4, provides a semi-quantitative screening view for comparing candidate HC applications under early-stage process-development conditions. The purpose of the map is not to provide final design values, but to support a structured first assessment of where HC is likely to create industrial value and where its benefit may be limited by process penalties.

HC is most attractive when the main process limitation is mass transfer, micromixing, interfacial renewal, oxidant contact, controlled disruption, or pretreatment. In these cases, cavitation-induced local turbulence, shear, microjetting, and enhanced interfacial contact can directly address the dominant bottleneck. HC is less attractive when the limiting factor is thermodynamic equilibrium, refractory mineralization, unavoidable downstream separation, product instability, or poor operability, because these constraints cannot usually be overcome by intensified mixing or local energy dissipation alone.

Figure 4 should be interpreted as a preliminary screening tool rather than as a final technology-selection chart. Its main function is to distinguish applications where HC can directly address the controlling bottleneck from cases where the dominant limitation lies outside the effective action range of cavitation.

High usefulness combined with low or moderate penalty pressure indicates the most promising development space, while high penalty pressure or low bottleneck relevance indicates that HC should only be considered after project-specific validation.

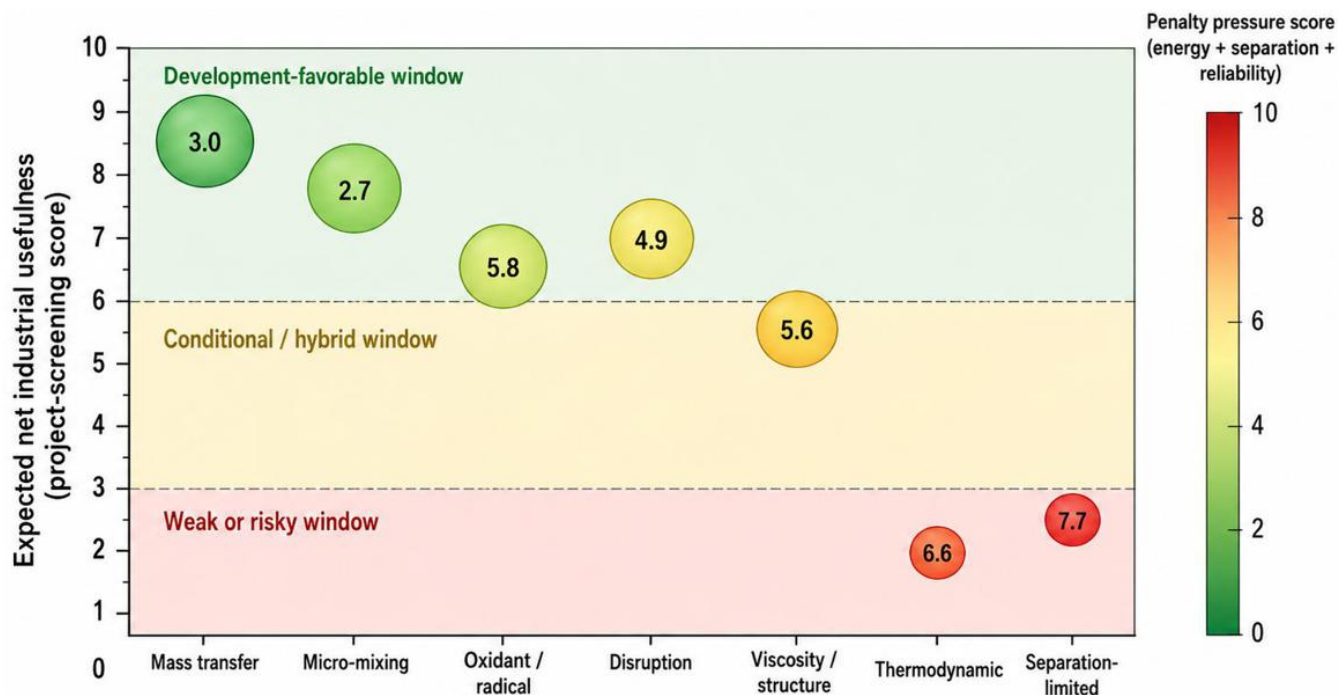


Figure 4. Hydrodynamic-cavitation Decision Landscape. Semi-quantitative screening map showing where HC is expected to be promising, conditional, or weak according to the dominant process bottleneck and expected penalty pressure. The y-axis represents expected net industrial usefulness on a 0–10 screening scale, where higher values indicate stronger expected bottleneck removal with retained flowsheet benefit. Bubble color and the numerical value inside each bubble indicate estimated penalty pressure from energy demand, separation burden, maintenance or materials risk, product-quality effects, and reliability or operability limits. Bubble size indicates how well the application has been experimentally validated and how confidently it can be scaled up. The values are illustrative and should be recalibrated using measured ENTM*, CNBI, separation-penalty, and reliability data for a defined project.

5.2 Multi-domain hydrodynamic-cavitation Regime Radar

The Multi-domain Hydrodynamic-Cavitation Regime Radar provides a comparative screening view of how different HC application domains perform across several engineering-relevant dimensions. Unlike a single performance indicator, the radar highlights the balance between useful cavitation effects and practical process constraints. This is important because a strong result in one dimension, such as high apparent conversion, intense droplet breakup, or rapid particle disruption, may be offset by weaker behavior in separation, energy use, product stability, reliability, or controllability.

The radar compares HC application domains across five screening dimensions: transport intensification, oxidation or activation potential, separation compatibility, energy efficiency, and reliability or controllability. These dimensions are selected because they represent the main factors that determine whether HC can provide a net process advantage beyond local intensification effects.

Figure 5 should therefore be interpreted as a profile-comparison tool rather than as a direct ranking of HC applications. Its main value is to show that different HC domains have different strength and limitation patterns. For example, biodiesel processing may benefit mainly from transport intensification and improved phase contact, whereas wastewater polishing may depend more strongly on matrix effects,

oxidant activation, and radical availability. Heavy-oil conditioning, in contrast, may be limited by product stability, viscosity rebound, fouling tendency, equipment erosion, and long-term reliability. For this reason, the radar scores should be recalibrated using measured project-specific data before they are used for process selection, scale-up decisions, or investment prioritization.

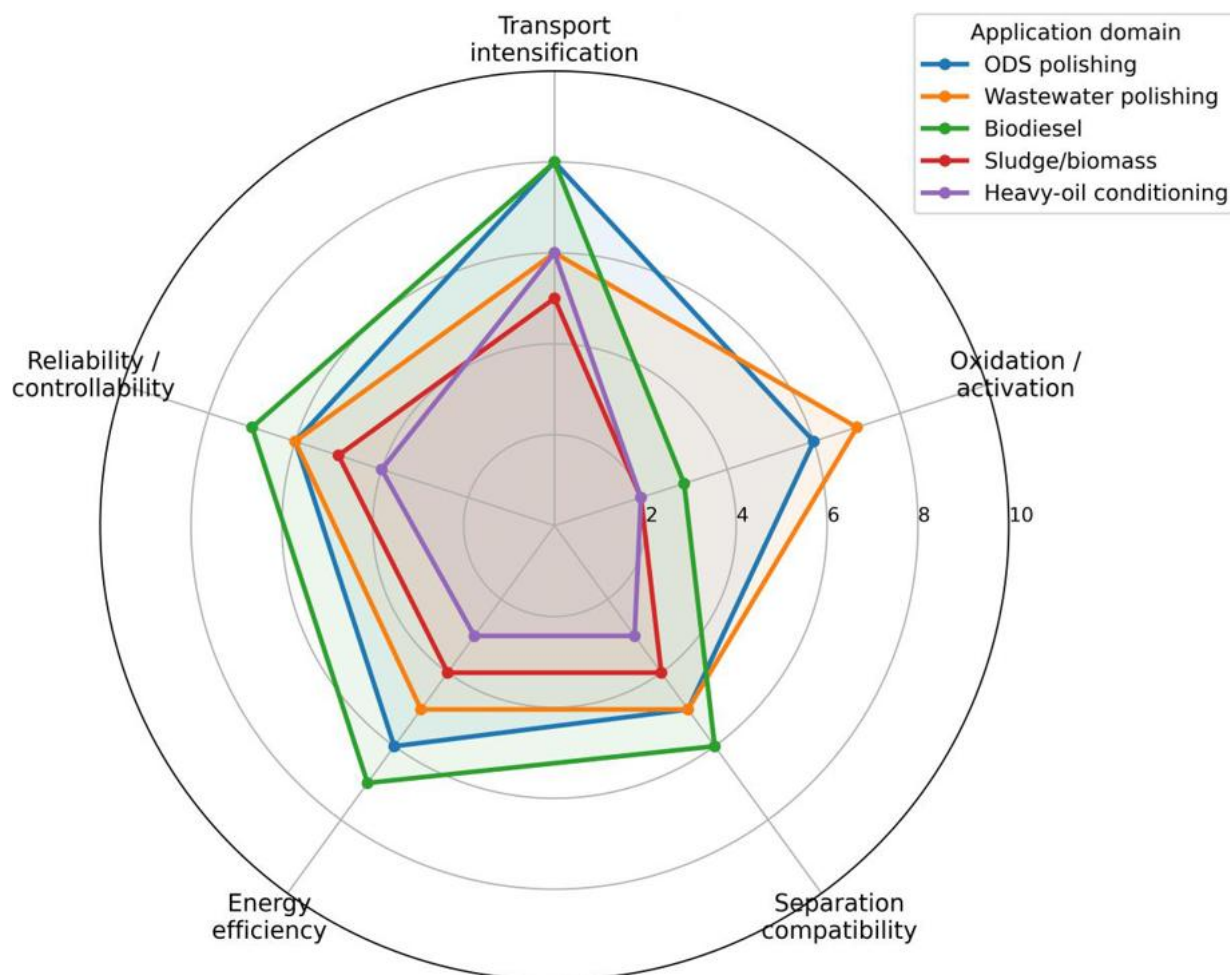


Figure 5. Multi-domain Hydrodynamic-Cavitation Regime Radar. Semi-quantitative screening radar comparing HC application domains across five engineering dimensions: transport intensification, oxidation or activation potential, separation compatibility, energy efficiency, and reliability or controllability. Higher scores indicate more favorable expected behavior in the corresponding dimension. The radar is intended for early-stage comparison of application profiles and should not be interpreted as a validated performance ranking unless the scores are recalibrated with measured project-specific data.

6. Regime map: when hydrodynamic cavitation is useful or weak

The regime map translates the Industrial Usefulness Window into HC-specific application guidance. It does not classify HC as generally useful or generally weak, and it does not assume that different HC concepts or commercial designs are interchangeable. Instead, it identifies the conditions under which HC is likely to remove the dominant process bottleneck and the conditions under which it is more likely to shift the burden to energy use, separation, product quality, maintenance, or reliability.

Table 3 summarizes the main HC application regimes in a compact decision-oriented format. For each regime, it distinguishes between conditions where cavitation can provide a defensible process benefit and conditions where the apparent intensification effect may be outweighed by downstream or operational

penalties. The final column defines the most realistic role of HC within an industrial flowsheet, with emphasis on integration rather than stand-alone performance claims.

Table 3. Compact hydrodynamic-cavitation regime map.

| Application regime | HC is useful when | HC is weak when | Most defensible role |
|--------------------------------------|------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------|
| Liquid-liquid reaction and ODS | Interfacial transfer limits reaction and products can be separated efficiently. | Equilibrium, oxidant cost, solvent loss, or emulsion stability dominates. | Inline contactor before extraction, adsorption, or polishing. |
| Biodiesel and renewable fuels | Alcohol-oil contact or micromixing limits residence time or conversion. | Glycerol separation, washing, catalyst removal, or product quality worsens. | Continuous intensified contactor with phase-separation control. |
| Wastewater polishing | Partial oxidation improves biodegradability, toxicity, color, odor, or target removal. | Complete mineralization is required from HC alone in a scavenging matrix. | Hybrid polishing or pretreatment module. |
| Sludge, biomass, and cell disruption | Controlled disruption improves digestion, extraction, sanitation, or biodegradability. | Dewatering, filtration, fouling, or polymer demand worsens. | Pretreatment before digestion, extraction, filtration, or dewatering. |
| Heavy oil and refinery integration | Retained pumpability, blending, heat transfer, desalting, or additive-use benefit is obtained. | Viscosity rebound, asphaltene instability, sediment, fouling, corrosion, or emulsion risk dominates. | Side-stream or inline conditioning module. |

Table 3 should be interpreted as a practical screening framework rather than as a universal ranking of HC applications. The strongest HC cases occur when cavitation directly improves transport, interfacial contact, micromixing, controlled disruption, or pretreatment while preserving a net flowsheet benefit. The weakest cases occur when the limiting step lies outside the useful cavitation field, such as thermodynamic equilibrium, unavoidable separation, refractory mineralization, product instability, or poor long-term operability. Therefore, each regime should be validated with project-specific data on energy demand, separation impact, product quality, equipment reliability, and integration with upstream and downstream unit operations.

7. Diagnostic case applications

The following diagnostic cases illustrate how the proposed framework converts hydrodynamic cavitation (HC) evaluation from a percentage-removal claim into a regime-based engineering diagnosis. The purpose is not to provide universal kinetic constants, but to show how measured or near-realistic data can be interpreted in terms of reaction limitation, mass-transfer limitation, matrix scavenging, energy demand, separation burden, and flowsheet usefulness. The numerical values used in the tables are illustrative engineering calculations and should be replaced by measured pilot or plant data for a specific feed, reactor, oxidant system, and process boundary.

7.1 Liquid-liquid oxidative desulfurization

Oxidative desulfurization (ODS) is a representative liquid-liquid reaction system in which hydrodynamic cavitation may be useful when interfacial transfer between the hydrocarbon phase and the oxidant-containing phase limits the apparent sulfur-conversion rate. In such systems, the relevant engineering

question is not whether the parent sulfur compound is oxidized, but whether sulfur is removed from the final fuel after extraction, adsorption, membrane separation, or polishing. Therefore, apparent conversion should be interpreted together with sulfur speciation, oxidant utilization, phase disengagement, solvent use, energy demand, and closed sulfur balance (Saylam, 2026c).

A simple diagnostic expression can be written by treating intrinsic oxidation and liquid-liquid mass transfer as two coupled resistances:

$$k_{\text{eff}} = \frac{k_{\text{rxn}}k_L a}{k_{\text{rxn}} + k_L a}$$

Equation 25. Diagnostic two-resistance relation between intrinsic oxidation and liquid-liquid mass transfer, where k_{rxn} is the apparent intrinsic oxidation-rate constant and $k_L a$ is the apparent volumetric liquid-liquid mass-transfer coefficient. The expression is equivalent to:

$$\frac{1}{k_{\text{eff}}} = \frac{1}{k_{\text{rxn}}} + \frac{1}{k_L a}$$

This expression should be used only as a regime-diagnosis approximation, not as a universal ODS kinetic law. It assumes constant apparent reaction rate, constant interfacial area, constant $k_L a$, negligible oxidant depletion, and no downstream separation limitation. These assumptions must be checked before the expression is used for design or scale-up (Saylam, 2026c).

Table 4 illustrates why maximum cavitation intensity is not automatically optimal. The assumed values show a transition from strongly transfer-limited behavior toward mixed reaction-transfer behavior. The 60 min conversion is calculated from:

$$X = 1 - \exp(-k_{\text{eff}}t)$$

Table 4. ODS diagnostic calculation showing diminishing return after the mass-transfer bottleneck is partly removed.

| Scenario | k_{rxn} (min^{-1}) | $k_L a$ (min^{-1}) | k_{eff} (min^{-1}) | 60 min conversion | Engineering interpretation |
|--------------|-------------------------------------------|----------------------------------|-------------------------------------------|----------------------|--------------------------------------------------------------------|
| Weak mixing | 0.08 | 0.015 | 0.0126 | 53% | Transfer-limited; HC may be useful. |
| Moderate HC | 0.08 | 0.060 | 0.0343 | 87% | Strong useful window if separation remains manageable. |
| Excessive HC | 0.08 | 0.090 | 0.0424 | 92% | Small extra conversion may not justify energy or emulsion penalty. |

The useful metric is therefore not sulfur oxidation alone. It is final sulfur removed from the treated fuel per unit delivered energy, oxidant dose, solvent use, phase-separation burden, and stable operating time. Once mass-transfer resistance is no longer dominant, additional cavitation severity may produce diminishing returns unless it also improves oxidant utilization, separation efficiency, or reactor reliability (Saylam, 2026c).

7.2 Wastewater polishing under matrix scavenging

Wastewater polishing is a different diagnostic case because the controlling limitation is often not only hydrodynamic contacting, but also radical scavenging by dissolved organic carbon, bicarbonate,

carbonate, nitrite, suspended solids, and other matrix constituents. Therefore, degradation rates measured in clean water should not be transferred directly to real secondary effluent or industrial wastewater. Cavitation-assisted advanced oxidation processes (AOPs) should be evaluated as polishing, pretreatment, or hybrid oxidation modules, especially when partial oxidation improves biodegradability, toxicity, odor, color, or target-micropollutant removal (Saylam, 2026a; Saylam, 2026b).

For an apparent first-order degradation process:

$$C(t) = C_0 \exp(-k_{\text{app}} t)$$

The time required for 80% target removal is obtained by setting:

$$\frac{C(t)}{C_0} = 0.20$$

Therefore:

$$0.20 = \exp(-k_{\text{app}} t_{80})$$

Then:

$$t_{80} = \frac{-\ln(0.20)}{k_{\text{app}}} = \frac{\ln(5)}{k_{\text{app}}}$$

Equation 26. Time required for 80% target removal under an apparent first-order rate constant k_{app} . Here, k_{app} is an observed process parameter that incorporates radical generation, matrix scavenging, oxidant transfer, hydrodynamics, and reactor-scale effects, rather than an intrinsic pollutant constant (Saylam, 2026b).

Table 5 gives a matrix-aware diagnostic calculation. The k_{app} values are illustrative apparent rates for a low-scavenging matrix, a high-scavenging matrix, and a case where HC improves apparent oxidant utilization. The calculation shows that decreasing k_{app} from 0.030 to 0.010 min^{-1} increases the required treatment time for 80% removal from approximately 54 to 161 min, which directly increases energy and oxidant demand.

Table 5. Matrix-aware HC-AOP diagnostic calculation based on apparent first-order removal.

| Matrix condition | k_{app} (min^{-1}) | t_{80} (min) | Design implication |
|---------------------------------|-------------------------------------------|-------------------|-------------------------------------------------------------------------------------------------------|
| Low-scavenging matrix | 0.030 | 54 | HC-AOP polishing may be plausible if energy and oxidant demand are acceptable. |
| High-scavenging matrix | 0.010 | 161 | Energy and oxidant demand are likely high; pretreatment or solids/DOC reduction may be needed. |
| HC-assisted oxidant utilization | 0.020 | 80 | Useful only if by-products, residual oxidant, filtration behavior, and reliability remain acceptable. |

This case should be linked to energy-normalized reporting. For example, Gostiša et al. (2021b) reported a rotating pinned-disc hydrodynamic cavitation case in which COD was reduced by about 31% after 15

liquid passes, with a specific energy consumption of approximately 8.2 kWh kg⁻¹ COD removed. Expressed as a reciprocal energy-normalized metric, this corresponds to:

$$\text{ENTM}_{\text{COD,HC}} = \frac{1}{8.2} = 0.122 \text{ kg COD kWh}^{-1}$$

This type of reporting is more useful than percentage removal alone because it connects apparent treatment performance to energy demand, matrix effects, and scale-up feasibility (Gostiša et al., 2021b; ISO, 2023; Saylam, 2026b). For wastewater applications, HC should therefore be described primarily as a polishing, pretreatment, or hybrid oxidation module rather than as a stand-alone mineralization technology. The required evidence should include COD, TOC, target-pollutant removal, toxicity, biodegradability, oxidant dose, by-product formation, residual oxidant, settling or filtration behavior, energy per mass removed, and stable operation under real feed variability (Gağol et al., 2018; Thanekar et al., 2018; Mancuso et al., 2020; Yeneneh et al., 2024; Saylam, 2026a, 2026b).

8. Industrial screening and validation pathway

Hydrodynamic cavitation, or any other process-intensification technology, should be screened as a family of candidate integrated process modules, not as a generic technology label or an isolated cavitation device. The first industrial question is which HC concept and configuration best remove the dominant bottleneck in the target flowsheet. The second question is whether the benefit remains positive after the relevant flowsheet-level penalties, uncertainty, and hard constraints are included. Where no available design provides an adequate fit, process-specific adaptation may be justified, but the adapted configuration must be evaluated as a new candidate.

Table 6. Compact industrial screening matrix for hydrodynamic cavitation applications.

| Application domain | HC is promising when | HC should be downgraded when | Minimum evidence |
|----------------------------------------------|----------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------|
| Oxidative desulfurization and fuel polishing | Liquid-liquid transfer limits sulfur removal and oxidized products can be separated efficiently. | Emulsion stability, solvent loss, oxidant cost, or phase separation dominates. | Final sulfur removal per kWh, oxidant dose, solvent use, phase-disengagement time. |
| Biodiesel and renewable fuels | Alcohol-oil contact or micromixing limits residence time or conversion. | Glycerol separation, washing, catalyst removal, or product quality worsens. | On-spec yield, separation time, washing demand, energy per product. |
| Wastewater polishing | Partial oxidation improves biodegradability, toxicity, odor, color, or target-pollutant removal. | Complete mineralization is expected from HC alone in a scavenging matrix. | COD/TOC or target removal per kWh, oxidant demand, toxicity, by-products, settling/filtration. |
| Sludge, biomass, and cell disruption | Controlled disruption improves digestion, extraction, sanitation, or biodegradability. | Dewatering, filtration, fouling, or polymer demand worsens. | Net downstream yield, dewaterability, soluble refractory organics, fouling tendency. |
| Heavy oil and refinery conditioning | Retained pumpability, blending, homogenization, heat transfer, desalting, or additive-use benefit is obtained. | Viscosity rebound, asphaltene instability, sediment, fouling, corrosion, or emulsion risk dominates. | Retained viscosity benefit, storage stability, desalting behavior, fouling, separation compatibility. |

Table 6 should be interpreted as a screening matrix rather than as a validated ranking of HC applications. Its entries summarize the most defensible application windows based on mechanism-bottleneck matching, but each case must be recalibrated with project-specific ENTM, ENTM*, CNBI, separation, product-quality, and reliability data. This requirement is consistent with matrix-aware AOP evaluation, where apparent performance depends on radical generation, scavenging, and reactor-scale transport, and with desulfurization regime analysis, where apparent conversion must be distinguished from final sulfur removal after separation (Saylam, 2026b; Saylam, 2026c).

The matrix should be used as a first-pass diagnostic filter. A promising entry does not justify implementation unless the selected device and operating condition improve the full process boundary. Conversely, a weak entry does not reject all cavitation concepts; it indicates that the currently proposed concept should be redesigned, hybridized, or compared against non-cavitating alternatives.

The validation pathway should follow a staged sequence. Each stage should narrow uncertainty and prevent local performance indicators from being mistaken for industrial usefulness.

Table 7. Validation pathway for hydrodynamic-cavitation process selection.

| Validation stage | Key question | Minimum evidence | Decision output |
|---------------------------------------|-------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------|
| 1. Define reference case and boundary | What conventional or alternative process performs the same duty? | Feed basis, product target, process boundary, baseline energy, chemical use, separation burden. | Valid reference case for ENTM, ENTM*, TNBI, or CNBI comparison. |
| 2. Identify dominant bottleneck | Is the limitation reaction, mass transfer, micromixing, dispersion, disruption, separation, or reliability? | Sensitivity to mixing, pressure drop, residence time, particle/droplet size, oxidant dose, temperature, and separation behavior. | Mechanism-bottleneck match or mismatch. |
| 3. Select or adapt HC concept | Which HC device class best addresses the bottleneck? | Cavitation number, pressure drop, flow rate, residence time, power density, temperature rise, materials compatibility. | Candidate HC configuration treated as a specific process module. |
| 4. Measure useful benefit | Does HC improve the useful output, not only local conversion or visible activity? | Final product quality, final sulfur removal, COD/TOC or target-pollutant removal, methane yield, retained viscosity, or on-spec yield. | Quantified useful output Y_{HC} . |
| 5. Quantify penalties | Does the benefit survive energy, chemical, separation, and maintenance burdens? | Delivered energy, oxidant/additive use, solvent losses, phase-disengagement time, fouling, erosion, downtime, product-quality loss. | Penalty factors and hard constraints. |
| 6. Calculate net index | Is the net benefit positive relative to the reference? | ENTM, ENTM*, TNBI or CNBI, reliability ratio, uncertainty bounds. | Accept, redesign, hybridize, or reject. |
| 7. Pilot under realistic variability | Does the benefit remain stable under real feed variability and long operating time? | Pilot-scale operation, repeated start-stop cycles, feed variability, cleaning demand, materials wear, control stability. | Scale-up decision with risk classification. |

A candidate passes validation only when the measured benefit remains positive on the full process boundary, not merely inside the cavitation unit. In practice, the most defensible HC applications will be those where the selected device removes a verified bottleneck at the minimum effective cavitation severity while preserving separation compatibility, product quality, reliability, and energy-normalized benefit.

9. Limitations, exclusion conditions, and failure modes

The proposed framework is not intended to promote hydrodynamic cavitation (HC), or any other process-intensification technology, as universally useful. Its value is diagnostic: it identifies when a specific HC concept and configuration should be developed, adapted, restricted to a defined duty, or rejected.

Important HC failure modes can be grouped into four categories. The first category is hydraulic and mechanical risk, including excessive cavitation intensity, vapor cushioning, excessive pressure drop, erosion, noise, and vibration. The second category is materials and maintenance risk, including corrosion, clogging, fouling, heat generation, short cleaning intervals, seal or bearing problems, and reduced availability. The third category is chemical risk, including decomposition of oxidants and other chemicals, formation of undesirable or hazardous intermediate or final products, incomplete mineralization, poor radical utilization, toxic transformation products, residual oxidant, and reagent overconsumption. The fourth category is separation and product-quality risk, including stable emulsion formation, poor dewatering, membrane fouling, product instability, viscosity rebound, asphaltene precipitation, sediment formation, solvent loss, catalyst damage, and loss of final product quality.

A candidate HC configuration should be downgraded, redesigned, or rejected when the dominant limitation lies outside the useful action range of cavitation. This includes cases where the controlling limitation is thermodynamic equilibrium; where complete mineralization is expected from HC alone in a strongly scavenging wastewater or biological matrix; where downstream separation is already the main bottleneck; where product quality or stability is degraded; where erosion or fouling rates are unacceptable; where availability is lower than that of the reference process; or where the apparent benefit disappears after storage, settling, filtration, extraction, washing, polishing, or operation with real feed.

A poor result from one HC design does not automatically reject the entire technology family, and a positive result from one design does not validate other designs. Transfer across device classes, geometries, or commercial versions is justified only when the relevant hydrodynamic mechanisms, operating envelope, and flowsheet penalties are shown to be comparable (Gogate and Pandit, 2000, 2001; Ranade, 2022; Zheng et al., 2022).

The same exclusion logic applies to other candidate technologies. A mixer should be downgraded if it creates over-dispersion, air entrainment, heat generation, or separation difficulty. A heat exchanger should be downgraded if heat recovery is offset by pressure drop, fouling, corrosion, cleaning frequency, or product degradation. A filtration system should be downgraded if improved solids capture is offset by rapid pressure-drop growth, fouling, short cleaning intervals, excessive consumable demand, or product loss. A reactor should be downgraded if higher conversion is offset by poor selectivity, heat-management risk, catalyst deactivation, unsafe operation, or downstream separation burden.

The main limitation of ENTM*, TNBI, CNBI, and the Industrial Usefulness Window is that they are reference-dependent. They depend on the selected reference case, useful-output definition, feed matrix, process boundary, penalty categories, uncertainty, and validation level. This is not a weakness. It is a safeguard against overclaiming.

10. Conclusions

This paper developed an energy-normalized and regime-based framework for judging when a specifically defined candidate process-intensification technology is industrially useful. The central conclusion is that local activity is not sufficient. Higher conversion, faster removal, stronger mixing, improved heat or mass transfer, visible cavitation, or higher operating intensity proves only that a technology produces an effect. Industrial usefulness requires that the useful benefit remains positive relative to a defined reference case after energy demand, chemical or consumable use, pressure drop, downstream separation, maintenance, product quality, reliability, uncertainty, and hard constraints are included.

The proposed Industrial Usefulness Window provides a practical operating-domain concept for this assessment. A candidate lies inside this window only when it removes the dominant process bottleneck without transferring excessive burden to other parts of the flowsheet. Because the window is configuration-specific, a technology family cannot be assigned a single universal usefulness judgment. Each relevant device, reactor, unit operation, conversion or reforming sub-process, or integrated module must therefore be evaluated as a distinct candidate on the basis of its governing mechanisms, operating envelope, process boundary, and flowsheet penalties.

The defensible development sequence is to identify the dominant bottleneck, select the concept and configuration that generate the required mechanism, adapt the selected design where necessary to the process duty, and then verify that the candidate remains inside its Industrial Usefulness Window. This sequence shifts evaluation from generic technology claims toward reference-based, energy-normalized, and reliability-aware process decisions.

Hydrodynamic cavitation was used as the main case study because it clearly illustrates the difference between physical activity and industrial value. HC can intensify micromixing, interfacial renewal, dispersion, oxidant contact, controlled disruption, and pretreatment. It is most defensible when these effects address the limiting step in the process. It becomes weak or risky when the dominant limitation is thermodynamic equilibrium, refractory mineralization, unavoidable downstream separation, product instability, material damage, fouling, or poor operability.

The analysis also shows that stronger cavitation is not automatically better. The preferred industrial target is the minimum effective cavitation severity that reproducibly removes the bottleneck while maintaining acceptable energy use, separation behavior, product quality, materials durability, controllability, and reliability. For this reason, HC should be selected, adapted where necessary, and developed mainly as an integrated reaction–transport–separation intensification module, not as a universal stand-alone treatment or upgrading technology.

More generally, the framework reframes technology evaluation from the question “does this technology class produce an effect?” to the more industrially relevant question “does this specifically defined, selected, and integrated candidate improve the complete process?” This distinction is essential for moving promising laboratory technologies toward credible pilot testing, scale-up, and industrial implementation.

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