Gas-Liquid and Liquid-Liquid Vortex Technology for Process Intensification

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Abstract

The quest for efficient, sustainable chemical processes drives the advancement of process intensification methods. This study evaluates vortex technology, which utilizes controlled, confined swirling flows to enhance mixing and mass and heat transfer, improving process efficiency. Its potential is assessed by examining its principles, design and optimization parameters, current and prospective applications, and challenges in scaling-up and commercialization. It is particularly suited when enhanced efficiency in mixing, transport performance, and cavitation is required, especially in systems involving fast reactions, short residence times, and space constraints. Furthermore, it shows promise in developing compact and efficient contacting devices with reduced energy consumption.

Keywords: Vortex technology, Mixing, Mass transfer, Heat transfer, Process Intensification

1. Introduction

Process Intensification (PI) refers to any technological advancement that leads to a smaller, cleaner, or more energy-efficient technology [1], essentially "achieving more with less" by enhancing production, quality, energy efficiency, processing time, or functionality while reducing equipment size and energy consumption [2]. In gas-liquid applications, specifically in transport-limited reactive systems, PI can overcome limitations in three key areas: (1) enhancing interphase mass transfer by increasing the mass transfer coefficient and interfacial area, which determine the overall mass transfer rate [3]; (2) accelerating mixing efficiency within a phase to optimize the reaction process by enhancing micromixing, i.e., mixture homogenization at micro-scale [4]; and (3) intensifying heat transfer, crucial for efficiently removing or supplying heat while maintaining optimal temperature profiles. An extreme physiochemical condition known as high gravity-based technology, or Higee, exemplified by the rotating packed bed (RPB), is a PI technology for chemical processes that use mechanical rotation to create centrifugal forces up to 1000 times stronger than gravity [4, 5]. For gas-liquid applications, the high gravity field generally generates fine droplets/bubbles and turbulent flow patterns. [2, 4, 6]. The contacting area is, therefore, significantly enlarged, and the mass transfer coefficient is increased, leading to improved efficiency and cost-effectiveness [2, 4, 7]. This study illustrates the enormous PI potential of vortex technology, exemplified by its static configuration. Compared to mechanically rotating PI technologies such as RPBs, vortex technology offers a simpler design, a safer and more stable operation, reduced maintenance costs, and potentially reduced energy consumption by eliminating mechanically rotating parts, utilizing confined swirling flows to achieve PI [8, 9].

Swirling flows can achieve PI by minimizing heat and mass transfer resistances and enhancing mixing [10]. They are characterized by a high tangential velocity component and angular momentum, inevitably linked to their rotational motion around an axis. Swirling flows are primarily generated through either mechanically induced rotation, e.g., using propellers and rotating pipes/beds, or by applying tangential injectors, stationary vanes, and twisted tapes in a unit [11]. In confined swirling flows, i.e. swirling flow generated in static devices without mechanical rotation, a strong centrifugal field is realized by converting pressure energy into intense swirling motion [10]. The high gravity, in combination with the radial static pressure gradient, induces flow stabilization and multiphase uniformity while increasing the interphase slip velocity, thus intensifying processes such as gravitational separation or mass and heat transfer exchange [10]. The potential of heat transfer enhancement through swirling flows has been previously demonstrated in heat exchanger systems, where the accelerated turbulence between the flow's core and the boundary layer promotes heat transfer efficiency [10]. The strength of the swirl, which determines the generated centrifugal force, is quantified by the swirl number, S_w, a dimensionless parameter, typically defined as the ratio of angular momentum flux to axial momentum flux [11] that has been widely adopted [12-14]. Experimental estimation of the S_w is challenging and often relies on simplified expressions, while numerical simulations are more efficient, as swirling flows can be accurately modeled [15]. Particularly, for accurate characterization of swirling flows in multiphase systems, such as gas-liquid systems, a two-phase swirl number has been proposed [11].

This short review examines the benefits, current status, and future potential of vortex technology for gas-liquid and liquid-liquid applications, with the vortex unit acting as a contacting device. In this review, vortex technology refers to applying controlled, confined swirling flows in a static unit, leveraging the benefits of enhanced mixing and mass and heat transfer, thereby improving process and energy efficiency. The mechanisms of vortex technology, its applications, and its potential to overcome traditional technology limitations will be explored.

2. Gas-Liquid and Liquid-Liquid Vortex Technology

While vortex technology is advancing, several questions remain unanswered. Gaining a more fundamental understanding of the transport mechanisms in vortex systems is needed to design innovative vortex configurations that further enhance PI. Current industrial applications of vortex technology must be explored, and the achieved process improvements must be evaluated to identify future potential. The challenges of scaling up need to be addressed, particularly those associated with the choice between increasing the size of the vortex unit or increasing the number of units operating in parallel. As illustrated in Figure 1, a framework is proposed to evaluate different items associated with the use of vortex technology in the chemical industry. For gas-liquid and liquid-liquid processes, more efficient mixing and mass and heat transfer are crucial to optimize the process efficiency. This review primarily addresses gas-liquid processes. Liquid-liquid processes are also considered, given the mixing and transport limitations analogy.

Tangential injection of gas and/or liquid is most commonly used to generate high-intensity, stable swirling flows in a static device by leveraging fluid pressure energy [10], thus creating a centrifugal force field [16, 17]. This technique intensifies the interaction between the injected flows, significantly accelerating mixing [12]. Tangential injection is often combined with other techniques to generate swirling flows. A countercurrent gas-liquid vortex flow can be generated when gas is tangentially injected in the bottom of the device while liquid is sprayed from the top, balancing the turbulent kinetic energy and pressure drop [17]. Swirling flows are found in pressure swirl atomizers, where the tangential entry of the liquid creates a low-pressure zone that induces air entrainment, leading to a liquid film breaking into ligaments and droplets [18, 19]. Tangential liquid injection in a self-suction jet reactor enhances the gas suction rate, leading to intensified gas-liquid mixing [20]. When tangential injection is combined with ultrasound irradiation, microbubbles are created and collapse, thus improving turbulence and mixing uniformity [21, 22].

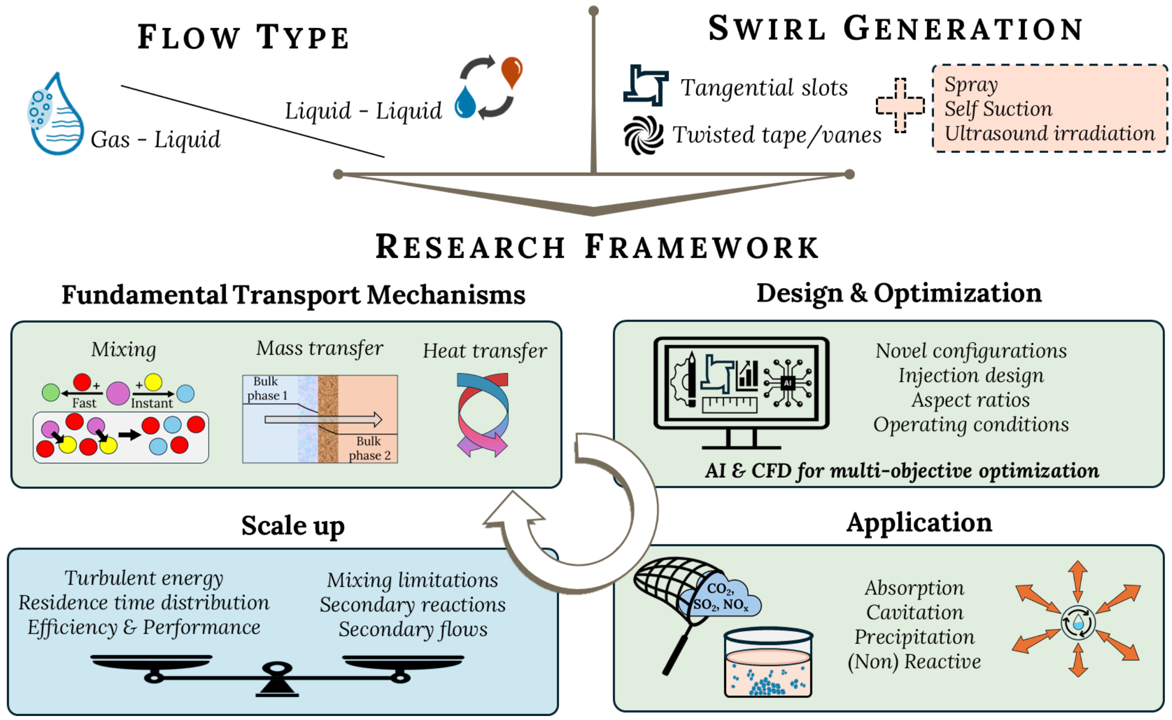

Figure 1. Research framework of gas-liquid and liquid-liquid vortex technology

2.1. Improving the understanding of transport mechanisms

Analyzing the transport mechanisms in vortex technology is essential to better understand improved mixing, mass transfer, and heat transfer. Tangential fluid injection results in micromixing times significantly lower than those in conventional mixers, and comparable to those in advanced technologies for gas-liquid [16] and liquid-liquid systems [23]. In fast reaction systems, efficient mixing is crucial to avoid undesirable side reactions, mitigate stagnant reactor zones, target a high uniformity of particle formation, and generally enhance efficiency.

The large radial velocity gradient in confined swirling flows indicates significant shear stresses and turbulence, resulting in enhanced interphase heat and mass transfer while reducing transport limitations [10, 21, 24, 25]. Turbulent kinetic energy in vortex flows is high, promoting mixing and generating a large and rapidly renewed interfacial area favorable for heat and mass transfer [8, 9]. For gas-liquid vortex units, high values of the overall (K_Ga) or liquid-side (k_La) mass transfer coefficient are reported by performing O_2, SO_2 or CO_2 absorption experiments [3, 8, 26, 27]. Duan et al. reported a threefold increase in the effective specific interfacial area with a hydro-jet cyclone compared to the values obtained in an RPB, reaching up to 5.4×10^3 m^2/m^3 [8]. Voinov et al. reported on an innovative static vortex device designed to intensify heat and mass transfer in an alcohol diabatic distillation column where vortex trays are inserted [28]. Dutta et al. achieved intensified heat and mass transfer for a CO_2 desorption application in a gas-liquid vortex unit reaching up to a CO_2 release rate of 2×10^4 $kg_{CO2}h^{-1}m^{-3}$, outperforming other conventional and intensified reactors such as packed beds and RPBs [29]. However, recent research has predominantly focused on intensifying mixing and mass transfer, focusing less on heat transfer enhancement.

Vortex chambers are typically oriented horizontally, with gas and/or liquid injections positioned at the same height. This design ensures symmetry in the internal forces applied within the chamber. The intense swirling motion generates a strong centrifugal field, leading to increased interphase slip velocities with typical gas-liquid vortex contactors achieving a centrifugal acceleration of 10-30 g [10], and advanced novel designs reaching up to 110 g [9]. Balancing flow residence time with vortex dynamics is crucial in vortex units: the formation of swirling flow patterns, centrifugal acceleration, and turbulence increase with increasing flow rates at the expense of a decreasing residence time [10]. Therefore, high flow rates can improve transport performance but potentially sacrifice the time needed to achieve high efficiencies [27, 30]. Short contact time can be advantageous in systems with fast reactions or when undesired, secondary, or side reactions occur. This trade-off implies that vortex technology might be unsuitable for processes requiring longer residence times. Furthermore, an increased pressure drop has been associated with swirling flows [11]. These shortcomings stimulate continuous development and optimization to further increase the range of applicability of vortex technology.

Several non-invasive visualization techniques have been utilized to investigate the hydrodynamics and visualize the swirling flow pattern, including Particle Image Velocimetry (PIV) [14, 24, 31], Laser Doppler Anemometry (LDA) [19] and Planar Laser-Induced Fluorescence (PLIF) [12]. High-speed cameras were employed in gas-liquid vortex unit studies to estimate liquid layer thickness [25, 32], bubble size distribution [26], and spray flow pattern [18, 19]. Computational fluid dynamic (CFD) simulations have also been performed to study and comprehend the hydrodynamics and interaction among transport mechanisms and reactions [9]. While solving the Navier-Stokes equations will accurately describe the fluid behavior, simulating the turbulence-chemistry interaction is more challenging due to the complex interplay between turbulent mixing and reaction kinetics [33]. Various turbulence models can be employed to simulate swirling flows, balancing accuracy and computational cost, especially in complicated multiphase systems. The applicable turbulence models include the Reynolds stress model (RSM), used for its accurate prediction of complex turbulent, anisotropic flow characteristics [13, 17, 22, 24, 27, 30]; the delayed detached eddy simulation (DDES), used for its accurate prediction at low computational cost [34, 35]; the two-equation k-ε RNG (Re-Normalization Group) model fit for capturing swirling flow characteristics [20, 36, 37]; and the Large Eddy Simulation (LES) method that provides detailed turbulence modeling at the expense of requiring excessive computational resources [12, 14].

2.2. Design and Optimization

Current research focuses on efficiently developing new vortex design concepts and optimizing existing ones using CFD, which helps to design, evaluate, and refine vortex configurations efficiently while conserving time and materials. Identifying key design parameters is crucial for geometrical optimization. The number, position, size, and inclination angle of the gas and liquid inlets and various aspect ratios of a vortex unit are considered to be highly influential [38] as they define tangential velocity distribution, flow rotation, energy dissipation, and, ultimately, transport (mixing, mass transfer, and heat transfer) efficiency [17, 39]. Novel reactor designs can significantly enhance performance. Chen et al. designed and optimized a gas-liquid vortex reactor design, achieving a threefold increase in gas-liquid contact time and an 85% reduction in energy consumption compared to a baseline vortex unit [40]. In addition, novel designs of gas-liquid reactors efficiently integrate mixing and separation to co-capture SO_2/CO_2 and SO_2/NO [27, 41]. Next to a geometrical optimization of the vortex unit, tuning the operating conditions, particularly the flow rates, is essential for realizing the desired centrifugal field, flow pattern, residence time, and transport efficiency. In precipitation applications, it determines the composition of the formed particles [42].

In addition to traditional CFD, Artificial Intelligence (AI)-driven optimization techniques, such as Genetic Algorithms (GAs), are increasingly used to automate the exploration of the above-listed design parameters and efficiently screen configurations for optimal solutions [43]. Parametrization of the vortex design needs careful preparation to provide sufficient design parameters while restricting the computational demand [43]. These more recent techniques will further accelerate the design process and enable the design of novel reactor configurations. Multi-objective optimization techniques were recently applied to reduce energy consumption and improve fluid mixing in stirred tanks [44, 45], thus showing potential for use in vortex unit design as well. Finally, automated mesh generation will result in more accurate CFD simulations. Tools like Pointwise® and OpenFOAM® ensure consistent mesh quality and can adaptively refine meshes based on simulation requirements, enhancing the reliability of the results [43].

2.3. Applications

The application potential is essential when designing a newly developing technology like the vortex technology. Nevertheless, any design can be tailored for a specific application. In turn, advanced manufacturing techniques, like additive manufacturing or Computer Numerical Control milling, enable a cost-effective and functional construction of complex designs [25, 46, 47]. Thus, implementing optimized, novel designs for various industrial applications becomes feasible. Additionally, coupling these manufacturing techniques with machine learning (ML)-assisted design techniques is becoming increasingly prevalent [46], leading to opportunities for creating new vortex units with enhanced performance.

Due to the flexibility of most design parameters, vortex technology becomes applicable for a broad range of processes. Chemical absorption and desorption processes have garnered significant attention, including CO_2 capture [8, 9, 29], desulfurization [30], and simultaneous removal of SO_2/CO_2 [27] or SO_2/NO [41], mostly for flue gas purification. As reactions are fast, increasing liquid-side or gas-side mass transfer rates poses the most significant challenge [8, 27, 41]. Liu et al. achieved a 10-fold increase of K_Ga in a gas cyclone-liquid jet absorption separator compared to conventional devices, reaching up to 0.0357 kmol m^{-3} kPa^{-1} s^{-1}, while maintaining sufficiently high removal efficiencies for SO_2 and NO [41]. A gas-liquid vortex reactor outperformed conventional and intensified devices in terms of CO_2 absorption and desorption rate per unit volume, demonstrating the PI potential of vortex technology in terms of equipment size reduction [9, 29]. Zhao et al. reported that a diameter reduction of up to 75% and a height/diameter ratio reduction of up to 65% can be achieved with a microscale vortex flow contactor compared to conventional wet scrubbers [27]. Notably, current studies on flue gas treatment with vortex technology report atmospheric operating conditions [9, 27, 30, 41]. However, given the potential benefits of higher pressures in enhancing absorption performance, investigating the effect of elevated pressure conditions on the hydrodynamics and absorption rates in vortex chambers presents a promising opportunity for future research.

Vortex technology was also evaluated for the generation of hydrodynamic cavitation, which is applied in wastewater treatment. Bubble collapsing results in high localized pressure and temperature, producing reactive radicals that rapidly degrade pollutants in water [48]. Vortex technology effectively generates hydrodynamic cavitation that produces microbubbles [49], outperforming conventional cavitation devices such as orifice and venturi systems [50], and showing various advantages such as reduced equipment erosion and a higher cavitational yield [51]. Patil et al. showed that, by generating solvent-assisted cavitation with a vortex-based diode, the cost for ammoniacal nitrogen removal was reduced by a factor of 2-3 compared to conventional hydrodynamic cavitation [50].

In liquid-liquid processes, vortex technology was evaluated for precipitation applications. Intensively swirling flows that are controlled by liquid flow rates enable efficient macro- and micromixing and advanced mass transfer [21, 23]. Vortex technology provides an efficient approach for continuous operation, allowing for good tuning of both formation and growth of the particles [52]. High turbulent shear stresses improve particle morphology, resulting in small particle size distribution (PSD) and high particle uniformity [13], while ensuring high productivity, low energy consumption, and a strong scalability potential [23, 42].

2.4. Scaling up

Vortex technology offers high throughput processing in a compact unit due to its high intensity and efficiency. However, scaling up to pilot- or industrial-scale will entail challenges. One of the primary challenges in scaling up is the reduction in vortex intensity inside the chamber, which can affect the gas-liquid contact efficiency [40]. Key considerations typically include ensuring flow uniformity, homogeneity, selectivity, similar chemical reaction rate, and desired dimensionless numbers [10]. For mixing applications, a constant turbulent energy dissipation rate and an appropriate residence time distribution (RTD) are needed due to the continuous nature of the process [53]. Maintaining consistent flow patterns is important, while attention is needed in mixing-limited or sensitive-to-secondary-reactions systems to preserve the benefits of PI at larger scales [53].

Increasing the size of the vortex unit could lead to complications like the formation of secondary flows, e.g., counterflow or backflow, due to swirl decay, which disrupts the desired flow pattern and reduces the efficiency of the process [54]. To mitigate these issues, smart design to maintain efficiency when scaling up or increasing the number of parallel vortex units could be considered [38]. That way, the benefits of the original design are preserved while flexibility, reliability, and consistency are offered on a pilot- or industrial scale. In gas-liquid applications, the high centrifugal force can cause the liquid layer to remain near the chamber walls, leaving unexploited space during scaling up. To address this, internals can be included to promote flow breakup, enhancing uniformity within the chamber [5].

More efforts are needed to address scaling challenges in vortex technology. Although CFD can be a valuable tool for scaling up, CFD model validation using experimental data obtained on lab- and small pilot-scale units remains necessary before extrapolating the model to full-scale systems [53]. While examining the challenges of scaling up vortex reactors, parallels can be drawn with those encountered in scaling up gas-solid vortex systems. A common issue is the channeling and the creation of unpredictable flow structures leading to inefficient phase contact [55]. In gas-solid vortex systems, increasing the length-to-diameter ratio has been proposed for efficient scale-up; a strategy that can be implemented in gas-liquid and liquid-liquid vortex chambers [56].

3. Vortex technology's future

The future of vortex technology largely depends on the success of the ongoing first wave of industrial applications. In addition, vortex technology has shown to be extremely versatile, highlighting its expanding potential for broader applications. Ma et al. proposed a novel process for biological nitrogen and phosphorus removal from municipal wastewater [57]. Liu et al. enhanced the removal of antibiotic residues in milk through ozonation in a vortex reactor. The vortex flow was found to intensify the ozone dispersion and dissolution in the liquid phase while strengthened by hydrodynamic cavitation [58]. Van Hoecke et al. proposed a novel swirling reactor for the dehydrogenation of liquid organic hydrogen carriers (LOHC) in a three-phase gas-liquid-solid (catalyst) system [59]. Due to intensified mixing and mass and heat transfer, efficient hydrogen removal was realized [59]. Mendez-Acosta et al. showed that a tubular swirling flow reactor has great potential to outperform a typical continuous stirred tank reactor (CSTR) for anaerobic dark fermentation, as the efficient mixing decreases hydrogen supersaturation and enhances hydrogen production [60].

Vortex technology is a suitable choice when efficient mixing and reduction of mass and heat transfer resistances are required (Figure 2). It is beneficial for applications necessitating short residence times. Due to the static nature of the vortex unit, it offers advantages such as a safe and simple operation, compact size, and modular, cost-efficient design. Vortex technology can show further potential in liquid-liquid extraction applications requiring efficient mixing and mass transfer [10]. Additionally, it could be valuable for distillation applications, leveraging the simultaneous heat and mass transfer enhancement, an area that warrants further exploration. To overcome current limitations, further experimental studies are required to systematically identify the correlation between the operating conditions and the stability of swirling flows as well as the key scale-up parameters for specific applications [10].

Comparing vortex technology with RPBs and static mixers, two PI technologies with similar operating principles and targets, i.e. heat and mass transfer enhancement, shows that vortex technology combines several advantages. It provides a static operation, avoiding the need for packing material, while leveraging the benefits of intensive swirling flows and high centrifugal forces. This also shows the advanced potential of the technology to achieve energy savings. Nevertheless, RPBs are more technologically mature, with proven scalability at technology readiness level (TRL) 7 [61, 62], whereas vortex technology is still developing in that regard.

Figure 2. Benefits and potential of vortex technology

4. Conclusions and Outlook

Vortex technology refers to the generation of high centrifugal force fields (Higee) by controlling confined swirling flows. The shear stresses and turbulence generated by the swirling flow enhance micromixing and create a large, rapidly renewed interfacial area, which decreases heat and mass transfer limitations. Application of vortex technology in gas-liquid and liquid-liquid processes leads to process intensifications, particularly for chemical processes requiring efficient mixing, high heat and mass transfer, short residence times or/and space efficiency. The static and simple design of vortex units provides great potential for a safe, low maintenance cost operation with high throughputs leading to increased productivity and great scalability prospects. CFD has been instrumental in studying hydrodynamics and turbulence in a vortex unit, unraveling the coupled transport-reaction process, and thus useful for designing and optimizing novel vortex configurations. Optimized key design parameters combined with optimized operating conditions aim at improving swirling flow pattern, interfacial contact area and time, and transport efficiency while reducing energy consumption and equipment size. Machine learning techniques can accelerate the design and optimization of the technology, while advanced manufacturing makes the realization of complex vortex designs feasible.

Vortex technology is evaluated for various applications, including flue gas purification, wastewater treatment, and particle synthesis, leveraging its unique characteristics. The technology shows great potential in developing compact and efficient contacting devices, achieving advanced performance in micromixing, mass and heat transfer, cavitational yields, energy consumption, and high particle growth uniformity. The insights in vortex technology keep growing. Ongoing research is essential to address scaling-up challenges for industrial applications and move toward commercialization.

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