ACS Omega
Open Access

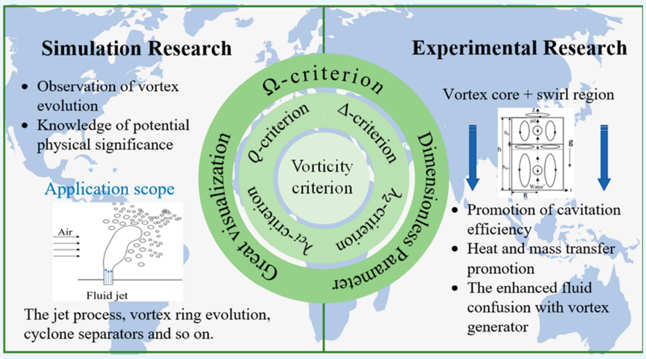
http://pubs.acs.org/journal/acsodf
Mini-Review

Eddy Current Identification Methods and Applications in the Chemical Industry: A Mini-Review

Xinjie Chai, Yingying Dong, Facheng Qiu,* Wensheng Li, Lei Zhang, Zhiliang Cheng,* Li Li, and Xingran Zhang

Cite This: *ACS Omega* 2024, 9, 8594–8600
Read Online

ABSTRACT: As one of the most common fluid patterns in the fluid flow process of chemical production, a vortex has been successfully demonstrated to be a structure that promotes interphase mixing and enhances heat and mass transfer. Therefore, it is essential to reveal the vortex evolution laws in order to realize more efficient and less energy-consuming chemical production. In this Mini-Review, the vortex identification criteria are introduced in detail and categorized according to their development history. The application of vortex identification technology and its application in the chemical industry are explored with a large number of examples. This review enhances our understanding of vortex structures and provides plenty of innovative ideas for the study of chemical industry production.



1. INTRODUCTION

Vortex physics is one of the most frequent physical phenomena in nature and daily life. In the field of fluid mechanics, vortices are three-dimensional highly turbulent dynamical systems. The formation of discrete unit-scale answer structures, such as droplets, is often accompanied by the formation of vortices. Intuitively, a vortex is the result of the rotational motion of a fluid. The nonlinear chaotic evolution process of vortices is manifested as steady and unsteady flows of water clusters stretching and compressing invariant sets. However, the nonstructural linear evolution within the fluid is difficult to be clearly recognized. Helmholtz[1] first proposed the vortex volume method to identify the vortex structure in order to reveal the complex flow structure of hydrodynamics. However, the concepts of "vortex" and "vorticity" have been confused for a long time, and there are misunderstandings about the vortex structure.

With the gradual improvement of eddy current identification methods, the evolution of the fluid flow pattern has been more deeply understood. High-efficiency mixing, energy-saving heat, and mass transfer have been the most concerning aspects in the field of chemical engineering. Multiscale vortex enable to change the fluid structure, enhance interphase mixing, and realize high-efficiency energy transfer and mass transfer.[2] Examples include the vortex mixer for micromixing and microreaction in channels and vessels,[3] vortex formation by stirring to achieve isentropic mixing to promote heat and mass transfer,[4] and so on. Vortex identification technology can not only improve the understanding of fluid flow but also provide effective guidance for chemical engineering applications and heat and mass transfer fields. Therefore, it is necessary to identify the vortex structure and study its application in chemical engineering.

The objectives of the research are given as follows:

1) The development of eddy current identification is analyzed and described, as well as the typical identification methods and its principle are introduced in detail.
2) Knowledge of eddy currents through numerical simulations, experiments, and visualization techniques.
3) The applications of eddy currents in the chemical industry are summarized in detail with practical examples.

Several commonly used eddy current identification methods are reviewed, with a focus on the application of eddy currents in the chemical industry. The whole review is organized as follows: the second part divides eddy current identification methods into three major categories according to their

Received: November 15, 2023
Revised: January 13, 2024
Accepted: January 25, 2024
Published: February 13, 2024

https://doi.org/10.1021/acsomega.3c09095
ACS Omega 2024, 9, 8594–8600

development history and focuses on several representative methods. The third part introduces the application of eddy currents in the chemical industry through both numerical simulation and experimental study and provides a brief summary of eddy current visualization techniques. The fourth part summarizes the whole paper and proposes directions for future research on eddy currents in the chemical industry.

2. CLASSIFICATION OF VORTEX IDENTIFICATION METHODS

2.1. The First Generation of the Vortex Identification Criterion. *2.1.1. Vorticity Criterion.* The mystery of vortices has always attracted extensive research by countless scholars. In 1858, Helmholtz was the first to unravel the mystery of vortices by defining the spin of a velocity vector as a vorticity, as shown in the following:[1]

$$\vec{\Omega} = \nabla \times \vec{V} \tag{1}$$

where $\vec{\Omega}$ is the vortex, ∇ is the vector differential operator, and $\vec{V}$ is the fluid velocity vector.

Helmholtz[1] proposed the vortex tube and vortex line to define the cyclonic motion in the flow field, and the vorticity was defined as a connected region in the flow field with a high concentration of vorticity, which is also known as the first generation of vortex definition. In addition, Helmholtz proposed the famous Helmholtz's three laws, i.e., in a nonviscous, positively pressurized fluid, if the external force is potential:

(1) The strength of the vorticity tube remains constant along the tube:

$$\oiint_S \vec{\Omega} dA = 0$$

where A is the area of any surface, and the unit is m^2.

(2) The strength of the vorticity tube does not change with time:

$$\frac{\mathrm{D}}{\mathrm{D}t}\left(\frac{\omega}{\rho}\right) = 0 \tag{3}$$

$$\frac{\mathrm{D}}{\mathrm{D}t}\left(\frac{\omega\theta}{\rho}\right) = 0 \tag{4}$$

Eq 3 is a two-dimensional fluid flow; ρ is the density, and the unit is kg/m^3, ω is the substance vortex, and the unit is kg m^3 s^{-1}.

(3) The direction of vorticity lines coincides with the direction of their material line flow.

All of the above descriptions use vorticity expressions instead of vortex. However, the vortex can be decomposed into rotating and nonrotating parts, and the vorticity can only express its size in a mathematical sense.[5] Therefore, vorticity cannot be fully expressed in terms of vortex. A vortex is both a rotating part and a vortex core part. Robinson et al.[6] found through their study that in the turbulent boundary layer, the strong vorticity region is weakly correlated with the actual vorticity region. In addition, the laminar motion in the pipe could explain this well. As shown in Figure 1, vorticity exists in the boundary layer of the pipe, but it does not produce vortices with fluid rotational motion. The tiny particles in this boundary layer can be seen as spin rather than vortex. Thus,

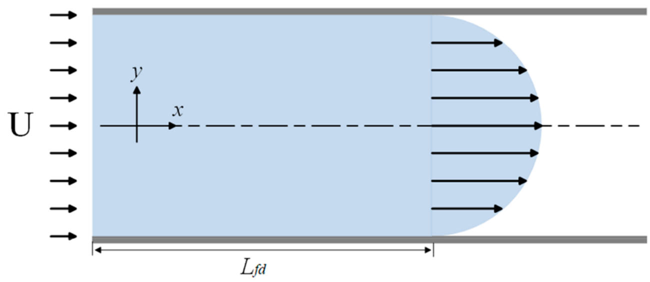


Figure 1. 2D laminar flow diagram.

Helmholtz has laid the cornerstone for the study of vortex dynamics, but the method of vortex identification still needs to be refined and improved.

2.2. The Second Generation of the Vortex Identification Criterion. In order to better understand the definition of vorticity and vortex and to study the fluid flow evolution and coherent vortex structure in the three-dimensional flow field, more vortex identification methods have been proposed by scholars. Based on the velocity gradient tensor expansion, the study of the second generation vortex identification criterion is opened.

2.2.1. Δ-Criterion. In the 1990s, Chong[7] found the existence of a connection between matrix properties and geometric features. Therefore, it is proposed to use the correlation values of 3 × 3 Jacobi matrices to describe the topology of the 3D flow pattern of the actual fluid flow process.

The system of three-dimensional matrix equations can be rewritten as a velocity gradient matrix:[5]

$$\nabla v = \begin{pmatrix} \frac{\partial u}{\partial x} & \frac{\partial u}{\partial y} & \frac{\partial u}{\partial z} \\ \frac{\partial v}{\partial x} & \frac{\partial v}{\partial y} & \frac{\partial v}{\partial z} \\ \frac{\partial w}{\partial x} & \frac{\partial w}{\partial y} & \frac{\partial w}{\partial z} \end{pmatrix} \tag{5}$$

where u, v, w are radial, tangential, and axial velocities, respectively.

$$\mathrm{P} = -tr(\nabla v) \tag{6}$$

$$\mathrm{Q} = \frac{1}{2}(tr(\nabla v)^2 - tr((\nabla v)^2)) \tag{7}$$

$$\mathrm{R} = -\det(\nabla v) \tag{8}$$

where P, Q, and R are the rotational invariant of the velocity gradient tensor ∇v and are dimensionless parameters. The Δ-criterion defines the region of complex conjugate eigenvalues, and the Δ-criterion is expressed as[8]

$$\Delta = \left(\frac{\mathrm{Q}}{3}\right)^3 + \left(\frac{\mathrm{R}}{2}\right)^2 \tag{9}$$

when $\Delta > 0$ represents the presence of vortices. The larger Δ is, the stronger the helical structure present in its vortex region.

2.2.2. λ_2-Criterion. The formular of the pressure-minimum criterion[9] is as follow:

$$\frac{\mathrm{D}S_{ij}}{\mathrm{D}t} - \nu S_{ij,kk} + \Omega_{ik}\Omega_{kj} + S_{ik}S_{kj} = -\frac{1}{\rho}P_{,ij} \tag{10}$$

https://doi.org/10.1021/acsomega.3c09095
ACS Omega 2024, 9, 8594−8600

where $\frac{DS_{ij}}{Dt}$ is unsteady irrotational straining and the unit is s^{-2}; $\nu S_{ij,kk}$ is viscosity and the unit is s^{-2}.

It has been found that the criterion cannot be derived with complete accuracy for vortices. It would be a necessary condition for the existence of vortices and not a sufficient condition. Therefore, Jeong[10] ignored the nonstationary effects and viscous strain in the N−S equation. The pressure minimum perpendicular to the plane of the vortex axis and the region with zero velocity gradient at that point are redefined as a vortex structure. The method determines the vortex existence by calculating the minimum eigenvalue of the velocity gradient tensor, which can identify the core structure of the vortex. Owing to the vortex structure, the domain where the correlation phase is negative is defined as the region where the vortex exists.

$$\lambda^3 + P\lambda^3 + Q\lambda + R = 0 \tag{11}$$

The above equation is solved for real numbers λ_1, λ_2, λ_3; if $\lambda_1 > 0 > \lambda_2 > \lambda_3$, this demonstrates the existence of a vortex structure at this location.

2.2.3. λ_{ci}-Criterion. The λ_2-criterion requires that its eigenvalues are all real numbers to be recognized. However, the eq 12 solution exists with complex eigenvalues. Zhou[11] proposed the λ_{ci} criterion for optimization to make up for the defect. The λ_{ci} criterion allows for localized vortex identification with the following expression:

$$\nabla v = [d_{ij}] = [v_r \quad v_{cr} \quad v_{ci}] \begin{bmatrix} \lambda_r & & \\ & \lambda_{cr} & \lambda_{ci} \\ & -\lambda_{ci} & \lambda_{cr} \end{bmatrix} [v_r \quad v_{cr} \quad v_{ci}]^{-1} \tag{12}$$

where the real eigenvalue λ_r has the eigenvector v_r, the conjugate complex eigenvalue $\lambda_{cr} \pm \lambda_{ci}$, and the conjugate complex eigenvector pairs are $v_{cr} \pm v_{ci}$. This criterion utilizes the imaginary part of the conjugate complex eigenvalue to visualize the local vortex and removes the dependence on the reference system. As a result, the vortex in the complex regions can be better recognized.

2.2.4. Q-Criterion. The Q-criterion uses the rotational invariant P of the velocity gradient tensor ∇v as a decision criterion for vortex identification. Hunt et al.[12] defined that in incompressible fluids, the vortex present in the region where the rotation rate tensor is larger than the strain rate tensor. Therefore, the method gives a better identification of vortex structures in fluctuating flow fields.

$$\Omega = \frac{1}{2}[\nabla v - (\nabla v)^T] \tag{13}$$

$$S = \frac{1}{2}[\nabla v + (\nabla v)^T] \tag{14}$$

$$Q = \frac{1}{2}[|\Omega|^2 - |S|^2] \tag{15}$$

where S is the strain rate tensor and Ω is the rotation rate tensor, and they are dimensionless parameters.

To refine the Q-criterion, the equation is usually standardized as follows:

$$Q_n = \sqrt{\frac{Q}{Q_{max}}} \tag{16}$$

where Q_n is the standard value and Q_{max} is the maximum value of Q.

The above studies have advanced the progress of fluid instability research. And yet, all of them are overly dependent on the selection of the threshold value. When large noise and numerical errors occur in the flow field, the extracted vortex structures are chaotically incorrect.

2.3. The Second Generation of the Vortex Identification Criterion.

2.3.1. Ω-Criterion. The Ω-criterion has good robustness and good noise reduction. It is able to recognize two- and three-dimensional flow fields well. Liu[13] proposed the Ω-criterion, which in turn visualizes the vorticity and can be understood as the concentration of the vortex. The vorticity part and the nonvorticity part of the vortex are introduced:

$$A = \frac{DS_{ij}}{Dt} + \Omega_{ik}\Omega_{kj} + S_{ik}S_{kj} \tag{17}$$

$$B = \frac{D\Omega_{ij}}{Dt} + \Omega_{ik}\Omega_{kj} + S_{ik}S_{kj} \tag{18}$$

where A and B are the symmetric and antisymmetric parts of the velocity gradient tensor ∇v and the units are s^{-2}. The sum of squares of the paradigms is introduced as follows:

$$a = \mathrm{trace}(A^T A) = \sum_{i=1}^{3}\sum_{j=1}^{3}(A_{ij})^2 \tag{19}$$

$$b = \mathrm{trace}(B^T B) = \sum_{i=1}^{3}\sum_{j=1}^{3}(B_{ij})^2 \tag{20}$$

The introduction of Ω denotes the ratio of its vortex fraction to the total vortex fraction

$$\Omega = \frac{a}{a + b} \tag{21}$$

where a and b are non-negative values and Ω takes values between 0 and 1. And the Ω is a nondimensional parameter. There is a correction factor of ε introduced to avoid division by zero.

$$\varepsilon = 0.001(b - a)_{max} \tag{22}$$

$$\Omega = \frac{a}{a + b + \varepsilon} \tag{23}$$

Deformation and vortex are not independent, and the shear strain rate decreases with an increasing vortex. Therefore, a Ω slightly greater than 0.52 can be used as a criterion for vorticity identification. Since the method has a clear physical meaning and is a dimensionless parameter. So, the criterion gets rid of the dependence on the threshold value and can capture the vortex coherent structure better.

3. VORTEX RESEARCH

3.1. Simulation Research.

Large vortex structures are characterized by complexity and chaos, and it is difficult to achieve qualitative and quantitative measurements of the instantaneous nonlinear motion of water particles due to the

https://doi.org/10.1021/acsomega.3c09095
ACS Omega 2024, 9, 8594−8600

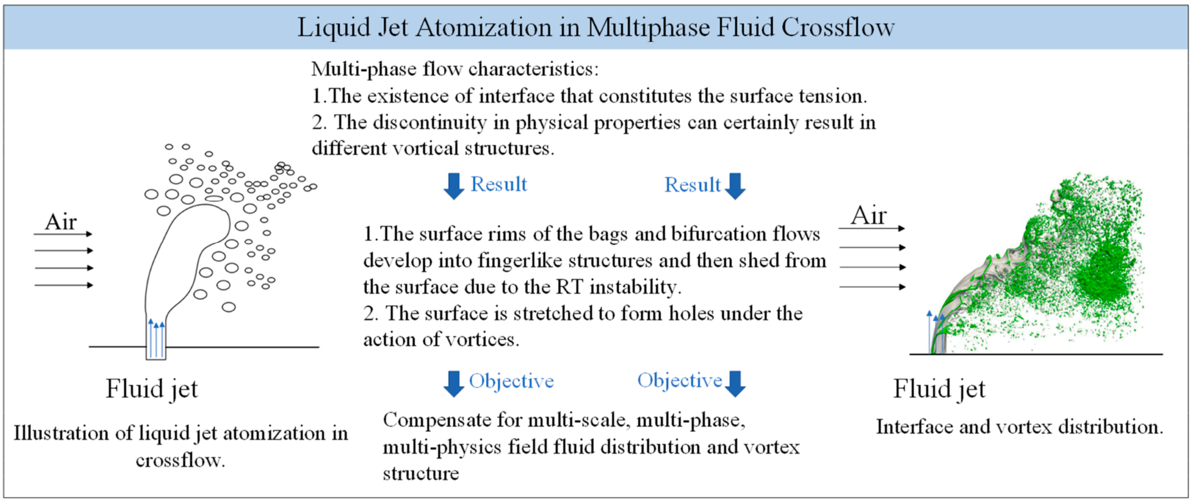


Figure 2. Two-phase fluid interface-vortex structure.

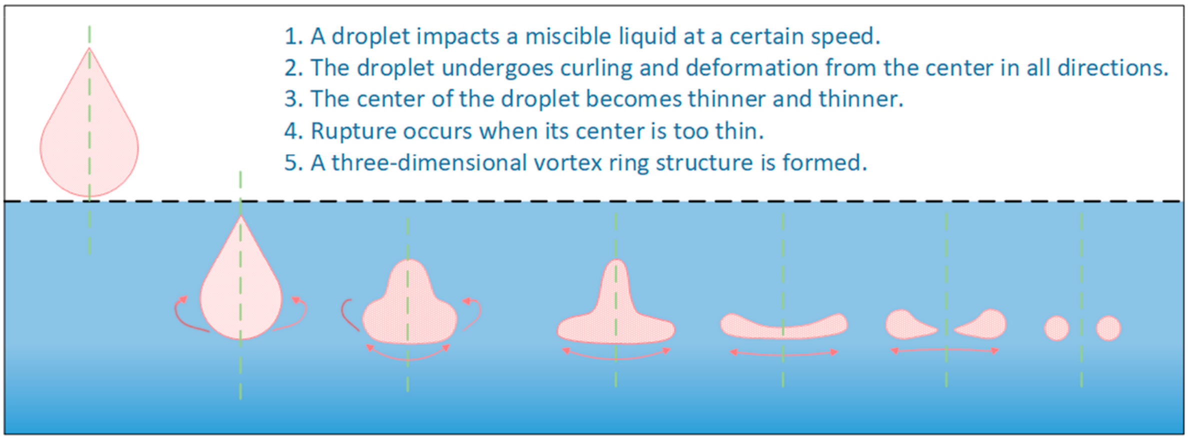


Figure 3. Two-dimensional plot of the vortex ring evolution of a liquid droplet impacting a water surface.

limited number of measurement techniques. It is also impossible to visualize vortex evolution in time-averaged flow fields and its underlying physical principles. Therefore, numerical simulation methods have been widely used in the field of studying the evolutionary structures of fluids. Hadžiabdić[14] revealed the spatiotemporal dynamic characteristics of vorticity and vorticity structure in the transient flow field of circular hole jet impingement with large eddy simulation. The vortex is also explored by identifying the vortex using the Q-criterion. The evolution of vortices causes pressure fluctuations inside the flow field, which induces the phenomenon of jet flutter. The flow field appears as a three-dimensional highly turbulent system to achieve high-efficiency heat and mass transfer between fluids. Chai[15] performed detailed numerical simulations of the atomization process of a cross-flow liquid jet using an analog simulation method. It is shown that the vortex promotes the formation of holes on the fluid surface. Similarly, Yoo[16] analyzed and studied the spray power field using a large vortex simulation technique. It was found that there were recirculation flows following the jet liquid column, containing horseshoe vortices, wake vortices, and reverse rotation vortices. The formation, growth, and dissipation of the interface-vortex are accompanied by an evolutionary process from liquid pocket crushing to ligament crushing in each strand, as shown in Figure 2. This results in the formation of numerous droplets of different sizes, which realizes the transfer of mass and energy.

The vortex ring is an annular region of fluid. When an aqueous droplet hits the surface of the fluid at a certain impact velocity, it begins to curl up along the perimeter. The vortex ring is not the result of a contraction rupture of the fluid system but rather a result of its natural imaging. As shown in Figure 3, the vortex structure similar to a "donut" shape was first proposed by An.[17] The structure has a larger gas−liquid phase boundary area, shorter diffusion distance, and better deformation capability than the conventional spherical structure. An used the vortex quantity method to capture a series of vortex ring-derived particles in his simulation studies and developed a general and robust method to generate vortex ring structures.

The cyclic switching of reversible hydroturbine operating modes results in confined pressure vortices and large pressure fluctuations. The Ω-criterion is used on reversible hydroturbine[18] to accurately identify strong and weak vortex within the impeller, enriching the understanding of the reversible turbine structure. Cyclone separators can realize the separation and purification of different substances by centrifugal force. They are widely used in chemical industry generation due to their low cost, ease of installation, and ability to be used in an extreme environment. The vortex core structure of the cyclone frequently deviates from the geometric center of the device

https://doi.org/10.1021/acsomega.3c09095
ACS Omega 2024, 9, 8594−8600

during operation. It greatly reduces the separation efficiency and also causes an unstable operation of the device. Zhang[19] performed simulation studies by using the RANS model. Dong[20] used the vortex identification methods such as the vortex-criterion, Q-criterion, and Ω-criterion to characterize the vortex flow field and used the vortex coherent structure to deepen the understanding of the cyclone separator device. The scholars analyzed the eccentricity at the vortex core from two dimensions, radial deviation and longitudinal deviation, and obtained the vortex core frequency and energy distributions by a fast Fourier transform (FFT). The results show that the skewness of the vortex core can be effectively reduced by increasing the inlet symmetry, while increasing the skewness of the vortex core can improve the collection efficiency for particles with diameters larger than 2.0 μm. Therefore, the understanding of the vortex coherent structure can provide guidance for the optimized design of chemical industry equipment, such as cyclone separators.

3.2. Experimental Research. Through a great number of simulation studies, it has been concluded that the correct application of the vortex can increase the chaos of unsteady flow and achieve an increase in the contact area between the phases. Therefore, scholars have decided to apply this conclusion to practical problems. The vortex is divided into a rotating part at the periphery and a vortex core part at the center. In order to better apply the vortex structure to industrial production, scholars have carried out in-depth exploration and research on these two parts of the structure, as shown in Figure 4. On the one hand, the vortex movement

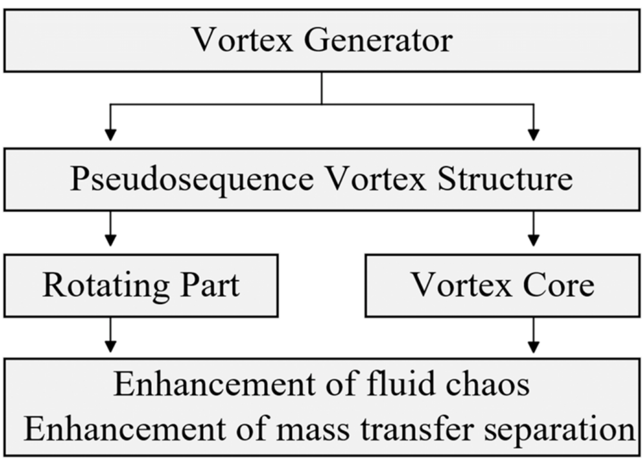


Figure 4. Flowchart.

has its unique flow characteristics, which can realize the transmission and mixing process between fluids. Different properties of the two liquids are immiscible, and the interphase boundary layer hinders heat and mass transfer between the two fluids. The unique motion characteristics of a vortex can break the limitation of the fluid boundary layer. Ozcan[21] found experimentally that polychlorinated biphenyls (PCBs) were efficiently transferred from the aqueous phase to the organic solvent phase due to the vortex structure. The aqueous phase was then separated from the organic solvent phase by using a centrifugal device to take advantage of the density difference between the two phases. Compared with conventional extraction, the coupling of vortex-assisted and liquid−liquid extraction not only improves the extraction efficiency but also reduces the working cost and environmental pollution. While stirring two immiscible liquids, it was discovered by Naumov[22] that the fluid develops a double vortex structure as shown in Figure 5. As the rotational intensity increases, the vortex topology strengthens, and the double vortex bubbles evolve and burst simultaneously. This process provides new ideas for mixing processes in chemical, biological, and pharmaceutical industries.

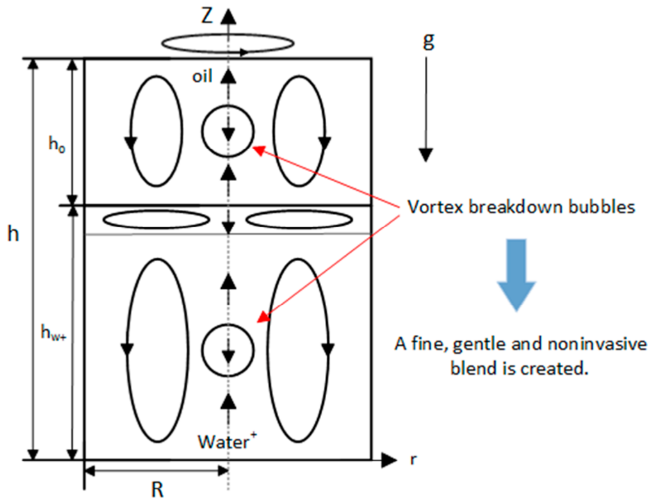


Figure 5. Double vortex breakdown phenomenon of two immiscible fluids.

On the other hand, the core of the vortex structure is located at the center of the vortex. This region has the lowest pressure, leading to the formation of a localized low-pressure region in the flow field. The operation of the turbine is affected by the localized pressure fluctuations in the vortex, and the cavity created by the low pressure seriously compromises the structural safety of the turbine. For the localized pressure drop region of the vortex structure, Patil[23] skillfully applied this feature by using vortex diodes in combination with aeration on a hydrodynamic cavitation device. Hydrodynamic cavitation requires the existence of a sufficiently low-pressure region within the fluid domain to allow for a certain collapsing strength of the fluid as it passes through the nozzle. The high rotational motion of the fluid inside the vortex diode provides the low-pressure region. The majority of traditional hydro-cavitation devices require an external energy source, such as ultrasound, to create a localized pressure drop, which greatly increases production costs. Experimentally, it was shown that the cavitation yield of the device for the removal of ammoniacal nitrogen from wastewater at a pressure of 0.5 bar was 261.0×10^{-4} mg/J. The cavitation yield of the vortex diode as a cavitation reactor was significantly increased by an order of magnitude compared with that of the conventional chemical industry.

In addition, vortex generators are used to enhance the fluid flow pattern and are mainly categorized into three main types: active, passive, and composite. The active vortex generators are generated spontaneously during the fluid flow. These technologies are advantageous in that they do not require external energy inputs and enable vortex formation and control in fluid pipes. One of the most typical vortex generators of the active technique is the raised structure of the pipe wall. The experimental results of surface oil visualization by Lo[24] showed that the vortex formed due to the raised surface of the pipe wall

https://doi.org/10.1021/acsomega.3c09095
ACS Omega 2024, 9, 8594−8600

can control the wake flow and thus reduce the intensity of the wake flow. On the other hand, the passive type generates vortices by adding a disturbance device in the fluid domain, and this vortex generator requires an external energy input to be realized. The advantage of the passive technique is the ability to adjust the strength and position of the vortices as needed to control and optimize the fluid. For example, Shelley[25] through experimentation studied the simulation of high-performance air-cooled radiators in the fluid domain with the addition of a flag structure, the fluid due to the dynamic response of the flag structure in the flow field and the generation of a vortex structure. It resulted in a significant enhancement of the average heat transfer coefficient in the flow field, thus realizing a high degree of fluid mixing in high-intensity heat and mass transfer, whereas the composite utilizes passive devices such as twisted bands, roughness primitives, etc. This results in high turbulence and strong eddy phenomena in the flow field to maximize heat and mass transfer. Whether active or passive, vortex generators can effectively improve fluid mixing and heat and mass transfer and increase the reaction efficiency of the reactor. Therefore, the vortex generator has a wide range of application prospects in the chemical process.

In the chemical industry, fluid flow is usually involved. One of the most frequently occurring phenomena in fluid flow is the vortex structure. The behavior of fluid structure and flow evolution directly influences heat and mass transfer and separation in the chemical industry. In addition, due to the fluid instability proposed sequential vortex structure, which can reduce the separation efficiency of the cyclone separator, the cavity easily forms and damages the experimental equipment. The local pressure drop effect of vortex technology combined with hydraulic cavitation promotes the cavitation yield. However, vortex structures studied in most of these studies were identified by camera shots or by CFD simulation of vortex knots without verifying that their vortex structures are complete and accurate. Therefore, the recognition of vortex structures through CFD techniques is the cornerstone of the research. Second, it is monitored through vortex visualization experiments. Finally, according to the vortex characteristics and vortex generator structure principle, the equipment is improved to realize more efficient separation and heat and mass transfer. The effects of reducing production cost and improving production efficiency can be achieved. The following conclusions can be drawn:

(1) It is necessary to select the appropriate eddy current identification criterion according to the applied engineering environment.
(2) A vortex-based cavitation reactor can be coupled with jet impingement technology to further realize the effect of interphase heat and mass transfer.
(3) The vortex generator can be used in chemical equipment such as cyclone separators to achieve better mixing effects or to suppress the generation of vortices, preventing damage to the equipment and prolonging its life.

4. CONCLUSION

This Mini-Review categorizes eddy current identification methods into three development stages and elaborates on the typical methods in each stage. The vortex identified by different identification techniques also varies, and the correct application of vortex identification techniques has a crucial effect on the identification of vortex structures. Furthermore, the application of vortex identification techniques in numerical simulations and experimental approaches to vortex studies are discussed. In order to study the vortex structure accurately, the integration of numerical simulation and experimental study will be a mainstream trend. The summary provides many new ideas for the application of eddy currents in the chemical industry.

■ ASSOCIATED CONTENT

Data Availability Statement

All the data supporting the findings of the study are available in the article.

■ AUTHOR INFORMATION

Corresponding Authors

Facheng Qiu − *college of Chemistry and Chemical Engineering, Chongqing University of Technology, Chongqing 400054, China;* orcid.org/0000-0002-9998-9175; Email: qiufachengandl@126.com

Zhiliang Cheng − *college of Chemistry and Chemical Engineering, Chongqing University of Technology, Chongqing 400054, China;* orcid.org/0000-0002-7453-9987; Email: purper@cqut.edu.cn

Authors

Xinjie Chai − *college of Chemistry and Chemical Engineering, Chongqing University of Technology, Chongqing 400054, China*

Yingying Dong − *college of Chemistry and Chemical Engineering, Chongqing University of Technology, Chongqing 400054, China*

Wensheng Li − *college of Chemistry and Chemical Engineering, Chongqing University of Technology, Chongqing 400054, China*

Lei Zhang − *college of Chemistry and Chemical Engineering, Chongqing University of Technology, Chongqing 400054, China*

Li Li − *college of Chemistry and Chemical Engineering, Chongqing University of Technology, Chongqing 400054, China;* orcid.org/0000-0002-1272-0342

Xingran Zhang − *college of Chemistry and Chemical Engineering, Chongqing University of Technology, Chongqing 400054, China;* orcid.org/0000-0001-6186-9613

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.3c09095

Notes

The authors declare no competing financial interest.

Biographies

Xinjie Chai is a master's student at the School of Chemistry and Chemical Engineering, Chongqing University of Technology. Her main research interests are flow state identification and regulation.

Yingying Dong is a master's student at the School of Chemistry and Chemical Engineering, Chongqing University of Technology. Her main research interest is in numerical simulation of three-dimensional flow fields.

Facheng Qiu is a professor in the Chongqing University of Science and Technology, Chongqing, China. His main research areas are chemical process intensification and reactor design optimization as well as numerical simulation for CFD calculations.

https://doi.org/10.1021/acsomega.3c09095
ACS Omega 2024, 9, 8594−8600

Wensheng Li is a professor in the Chongqing University of Technology. His main research areas are resource and environmental chemistry, hydrometallurgy, and chemical economics.

Lei Zhang is an associate professor in the Chongqing University of Technology. His main research areas are algal culture and high-fat liquefaction technology.

Zhiliang Cheng is an associate professor in the Chongqing University of Technology. His main research areas are special wastewater treatment and resource utilization, industrial solid waste resource utilization and preparation and application of environmental catalytic materials such as reactive ceramic membranes.

Li Li is a senior engineer in the Chongqing University of Technology. His main research areas are materials chemistry and chemical process intensification.

Xingran Zhang is an associate professor in the Chongqing University of Technology. His main research areas are resource and environmental chemistry and hydrometallurgy.

■ ACKNOWLEDGMENTS

The study was supported by project of Chongqing Natural Science Foundation Innovation and Development Joint Fund (CSTB2023NSCQ-LZX0095), Scientific Research Foundation of Chongqing University of Technology, Science and Technology Research Program of Chongqing MuniciPal Education Commission of China (KJQN202001112) and Natural Science Foundation of Chongqing, China (cstc2021jcyj-msxmX0184), Postgraduate Innovation Project of Chongqing University of Technology (gzlcx 20232048).

■ REFERENCES

(1) Helmholtz, H. Über Integrale der hydrodynamischen Gleichungen, welche den Wirbelbewegungen entsprechen. *Journal für die reine und angewandte Mathematik* **1858**, *55*, 25−55.
(2) Yang, M.; Liu, S.; Xu, W. -h.; Xu, J. -y. Numerical and Experimental Studies of an Oil Slick Recovery Method That Uses a Free Surface Vortex. *ACS Omega* **2020**, *5* (48), 31332−31341.
(3) Feng, X.; Ren, Y.; Sun, H.; Chen, X.; Zhang, K.; Jia, Y.; Hou, L.; Xiao, M.; Jiang, H. Effect of vortex on mass transport and mixing in microcapillary channels. *Chemical Engineering Journal* **2019**, *362*, 442−452.
(4) Tang, X.; Qiu, F.; Li, H.; Zhang, Q.; Quan, X.; Tao, C.; Wang, Y.; Liu, Z. Investigation of the Intensified Chaotic Mixing and Flow Structures Evolution Mechanism in Stirred Reactor with Torsional Rigid-Flexible Impeller. *Industrial And Engineering Chemistry Research* **2023**, *62* (4), 1984−1996.
(5) Tian, S.; Gao, Y.; Dong, X.; Liu, C. Definitions of vortex vector and vortex. *J. Fluid Mech.* **2018**, *849*, 312−339.
(6) Robinson, S. K. A Review of Vortex Structures and Associated Coherent Motions in Turbulent Boundary Layers. *Structure of Turbulence and Drag Reduction* **1990**, 23.
(7) Chong, M. S.; Perry, A. E.; Cantwell, B. J. A general classification of three-dimensional flow fields. *Physics of Fluids A* **1990**, *2*, 765.
(8) Zhang, Y.; Liu, K.; Xian, H.; Du, X. A review of methods for vortex identification in hydroturbines. *Renewable and Sustainable Energy Reviews* **2018**, *81*, 1269−1285.
(9) Kline, S. J.; Robinson, S. K. Turbulent Boundary Layer Structure: Progress, Status, and Challenges. *Structure of Turbulence and Drag Reduction* **1990**, 3−22.
(10) Jeong, J.; Hussain, F. On the identification of a vortex. *J. Fluid Mech.* **1995**, *285*, 69−94.
(11) Zhou, J.; Adrian, R. J.; Balachandar, S.; Kendall, T. M. Mechanisms for generating coherent packets of hairpin vortices in channel flow. *J. Fluid Mech.* **1999**, *387*, 353−396.
(12) Hunt, J. C. R.; Wray, A. A.; Moin, P. Eddies, streams, and convergence zones in turbulent flows. *Studying Turbulence Using Numerical Simulation Databases, 2. Proceedings of the 1988 Summer Program*, 1988.
(13) Liu, C.; Wang, Y.; Yang, Y.; Duan, Z. New omega vortex identification method. *Science China Physics, Mechanics & Astronomy* **2016**, *59* (8), 684711.
(14) Hadžiabdić, M.; Hanjalić, K. Vortical structures and heat transfer in a round impinging jet. *J. Fluid Mech.* **2008**, *596*, 221−260.
(15) Chai, M.; Fu, Y.; Zheng, S.; Hong, Z.; Shao, C.; Luo, K.; Fan, J. Detailed numerical simulation of multi-scale interface-vortex interactions of liquid jet atomization in crossflow. *International Journal of Multiphase Flow* **2023**, *161*, 104390.
(16) Yoo, Y.-L.; Han, D.-H.; Hong, J.-S.; Sung, H.-G. A large eddy simulation of the breakup and atomization of a liquid jet into a cross turbulent flow at various spray conditions. *Int. J. Heat Mass Transfer* **2017**, *112*, 97−112.
(17) An, D.; Warning, A.; Yancey, K. G.; Chang, C.-T.; Kern, V. R.; Datta, A. K.; Steen, P. H.; Luo, D.; Ma, M. Mass production of shaped particles through vortex ring freezing. *Nat. Commun.* **2016**, *7* (1), 12401.
(18) Zhang, Y.-n.; Liu, K. -h.; Li, J.-w.; Xian, H. -z.; Du, X. -z. Analysis of the vortices in the inner flow of reversible pump turbine with the new omega vortex identification method. *Journal of Hydrodynamics* **2018**, *30* (3), 463−469.
(19) Zhang, Z.; Dong, S.; Jin, R.; Dong, K.; Hou, L. a.; Wang, B. Vortex characteristics of a gas cyclone determined with different vortex identification methods. *Powder Technol.* **2022**, *404*, 117370.
(20) Dong, S.; Jiang, Y.; Jin, R.; Dong, K.; Wang, B. Numerical study of vortex eccentricity in a gas cyclone. *Applied Mathematical Modelling* **2020**, *80*, 683−701.
(21) Ozcan, S. Analyses of polychlorinated biphenyls in waters and wastewaters using vortex-assisted liquid-liquid microextraction and gas chromatography-mass spectrometry. *J. Sep. Sci.* **2011**, *34*, 574.
(22) Naumov, I. V.; Sharifullin, B. R.; Tsoy, M. A.; Shtern, V. N. Dual vortex breakdown in a two-fluid confined flow. *Phys. Fluids* **2020**, *32* (6), No. 061706.
(23) Patil, P. B.; Bhandari, V. M.; Ranade, V. V. Improving efficiency for removal of ammoniacal nitrogen from wastewaters using hydrodynamic cavitation. *Ultrasonics Sonochemistry* **2021**, *70*, 105306.
(24) Lo, K. H.; Kontis, K. Supersonic flow over rounded contour bumps with vortex generators or passive longitudinal jets. *Experimental Thermal and Fluid Science* **2017**, *85*, 213−228.
(25) Shelley, M. J.; Zhang, J. Flapping and Bending Bodies Interacting with Fluid Flows. *Annu. Rev. Fluid Mech.* **2011**, *43* (1), 449−465.