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# Mini-review of capillary-gas-treating bioreactors: opportunities and challenges

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Mass transfer in gas–liquid contactors requires energy input (e.g., mixing or pressure drop) and is a critical parameter for the design and application of process equipment. Efforts in the engineering of less energy-intensive reactors to enhance mass transfer rate are key in biological gas-liquid reactors that treat hydrophobic gaseous compounds. Mass transfer coefficients ( $K_La$ ) in capillary reactors may be between one or two orders of magnitude higher than in conventional gas–liquid contactors. In this context, environmental abatement processes typically implemented in bioscrubbers or biotrickling filters, as well as industrial fermentation processes using airlift or stirred tank bioreactors containing cell cultures that are mass-transfer limited, could benefit from a capillary gas bioreactor configuration using a macro-channel (>1 mm internal diameter). This review discusses capillary reactors which can combine good mass transfer with relatively low pressure drop—two important factors affecting the cost-effectiveness of many industrial applications of biological gas treatment/processing systems.

## KEYWORDS

capillary bioreactor, gas treatment, mass transfer, segmented flow, Taylor flow, biological gas treatment, gas-phase biorefineries

## 1 Introduction

New fundamental concepts are needed to enhance the biological treatment of hydrophobic gases to more effectively improve air quality, reduce greenhouse gas emissions, and boost the economic feasibility of gas-phase biorefineries that convert gaseous streams containing methane, carbon monoxide, carbon dioxide, or hydrogen into higher value products such as fertilizers, biodegradable polymers, liquid biofuels, and fine chemicals (Lopez et al., 2018; Kennes and Veiga, 2013; Kraakman et al., 2025a).

Biological methods are being increasingly used to treat polluted airstreams or convert gases, as they are considered a more environmentally and, typically, cost-effective alternative to traditional physical-chemical gas treatment methods based on their higher energy and resource utilization efficiency. Nonetheless, biological gas treatment processes are inherently constrained by the gas–liquid mass transfer of hydrophobic gaseous compounds (Kraakman et al., 2011; Soreanu and Dumont, 2020). Enhancing mass transfer from the gas phase to a liquid containing the target compound converting

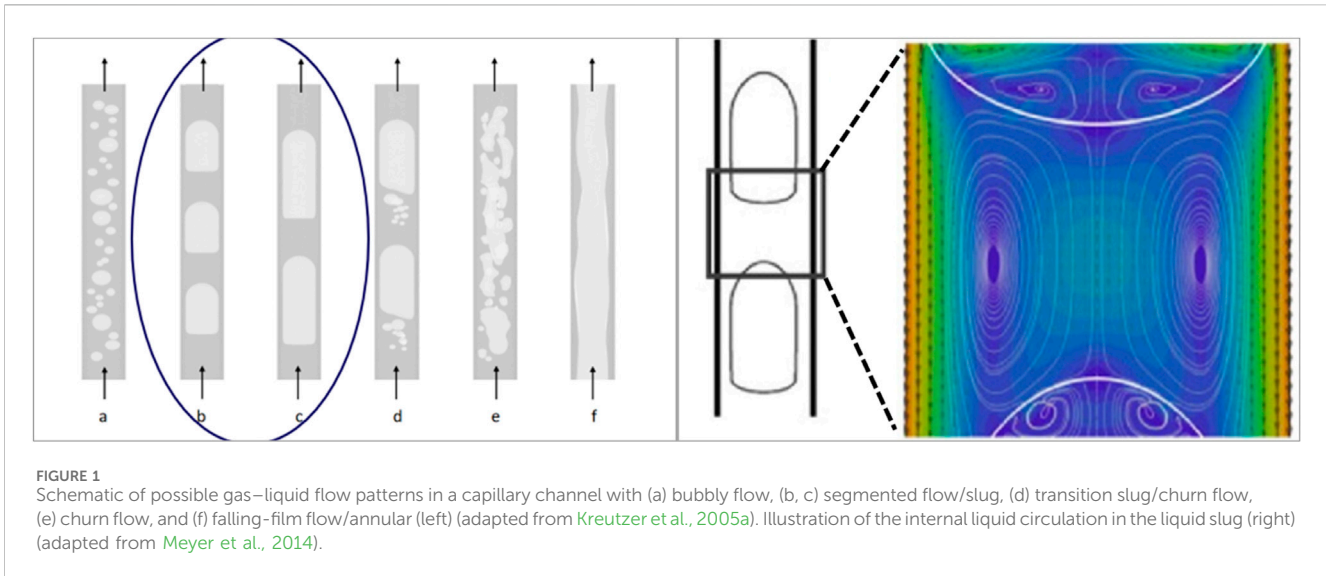


FIGURE 1

Schematic of possible gas–liquid flow patterns in a capillary channel with (a) bubbly flow, (b, c) segmented flow/slug, (d) transition slug/churn flow, (e) churn flow, and (f) falling-film flow/annular (left) (adapted from Kreutzer et al., 2005a). Illustration of the internal liquid circulation in the liquid slug (right) (adapted from Meyer et al., 2014).

microorganisms requires energy input (e.g., mixing or pressure drop), while power consumption is a key parameter for economically sustainable applications.

In this context, capillary reactors can combine good mass transfer with relatively low pressure drop—two important factors in the cost-effectiveness of industrial gas treatment/processing applications. The concept of a capillary-gas-treating bioreactor will be reviewed here.

## 2 Capillary gas–liquid Taylor flow

The typical flow patterns observed in capillary channels are bubbly, segmented, and annular (or falling-film) flow (Figure 1). The flow regime determines the level of turbulence and the interfacial areas between the gas and liquid phase that dictate the mass transfer rate. The gas–liquid flow pattern for optimal mass transfer is the segmented flow pattern, also called “slug flow,” “bubble-train flow” or “Taylor flow,” and is characterized by alternating gas bubbles and liquid slugs with lengths greater than the capillary diameter. Capillary gas–liquid contactors operating at an explicit gas–liquid flow pattern can create short distances in small (capillary) channels between the gas and liquid and an internal liquid circulation that enhances mass transfer. This segmented gas–liquid flow pattern has been reported to yield superior heat and mass transfer rates (Peng et al., 2022; Haase et al., 2016; Kreutzer et al., 2005a). Moreover, capillary forces are dominant in the capillary channel over other forces such as gravity and viscosity, which result in minimum pressure drop, requiring reduced energy to move the air and liquid through the channels (Kreutzer et al., 2005a; Liu et al., 2005; Zhang et al., 2017; Kraakman et al., 2011; Kraakman et al., 2025b).

## 3 Capillary action

Capillary action is the process of a liquid flowing in a narrow space without the assistance of, or even in opposition to, any external forces like gravity (Zhang et al., 2017). Building on this action,

capillary gas–liquid contactors support low pressure losses when gas flows through a capillary channel because capillary forces can become dominant over gravity forces when the channel diameter is small enough, while at the same time energy is not required to maintain small gas bubble sizes. Once the gas bubbles are formed in capillary channels, they typically do not merge, and therefore no turbulent energy is required to break them up into smaller bubbles. As the channel diameter decreases, capillary forces that have no influence in large diameter channels can become dominant. Capillary forces pull up liquids in narrow tubes or in porous materials such as paper and sand. This occurs due to intermolecular forces between the liquid and the surrounding solid surfaces. When the diameter of the channel is sufficiently small, the combination of surface tension (caused by cohesive forces within the liquid) and adhesive forces between the liquid and container wall drives the liquid upward against gravity. The mass transfer rate in a capillary reactor is therefore relatively energy-efficient and could be one order of magnitude higher per volume of gas treated than commonly used biotechnologies for gas treatment, such as bubble column reactors and biotrickle filtration (Kraakman et al., 2011).

Surface tension plays a critical role in the phenomenon of capillarity. This refers to the tendency of a liquid surface to minimize its surface area due to cohesive molecular forces. This property enables objects with a higher density than water (e.g., certain insects and thin metal blades) to float on a water surface. Because of the relatively high attraction of water molecules to each other through a network of hydrogen bonds, water exhibits a surface tension significantly higher than that of most other liquids. Capillarity is expressed by capillary number ( $Ca = \mu \times v/\gamma$ )—the ratio of viscous drag forces to its surface tension forces, with  $\mu$  standing for viscosity (Pa s),  $v$  for velocity ( $m\ s^{-1}$ ), and  $\gamma$  for the surface tension of the liquid ( $N\ m^{-1}$ ).

The dominance of the surface tension over other forces such as gravity is required to obtain segmented flow by capillarity. The Bond ( $Bo$ ) number is the ratio of the gravitational force to the surface tension force (Equation 1); a low value  $Bo$  number indicates that the surface tension dominates in a system:

$$Bo = \rho \times g \times d^2 / \gamma, \quad (1)$$

where  $\rho$  is the liquid density ( $\text{kg m}^{-3}$ ),  $g$  is the gravitational constant ( $\text{m s}^{-2}$ ), and  $d$  is the inner diameter (ID) of the capillary channel (m). A Bo number lower than 3.3 is required to obtain a segmented air–water flow pattern in a single channel. This threshold would be achieved for a capillary channel with an ID of less than approximately 5 mm while using water and ambient air at room temperature (Kreutzer et al., 2005a). However, the presence of salt media and biomass (compared to demineralized water) impacts the surface tension and therefore narrows the range of gas–liquid conditions for which segmented flow can be maintained in the capillaries (Kraakman et al., 2023).

## 4 Mass transfer

In the segmented (Taylor) flow regime, the short diffusion length within the gas phase and circulating vortices inside the liquid slug provide excellent gas–liquid mass transfer. Mass transfer of the target gaseous compound happens predominately from the gas phase to the liquid film along the channel wall through short-distance diffusion and from the liquid film to the liquid slugs through local mixing within the liquid slug. The segmented flow enables high mass transfer to take place at relatively low gas flow velocities ( $<1 \text{ m s}^{-1}$ ) and very short gas contact times (seconds) under various gas-to-liquid ratios with low axial dispersion.

Theoretical analysis of mass transfer in a capillary channel showed that the contribution via the liquid film surrounding the gas bubble was at least one magnitude larger than the contribution via the gas bubble caps for a capillary reactor containing gaseous methane and water (Bordel et al., 2024). This is consistent with the predicted correlation of van Baten and Krishna (2004) and with measurements by Dietrich et al. (2013).

The lengths of the gas bubbles and liquid slugs are critical as they determine the interfacial mass transfer area, as well as the mass carrying capacity of the liquid film along the channel wall each time a gas bubble passes by. The mass transfer may be seen as “a bucket on a conveyor belt”, where the liquid film (bucket) is filled every time a gas bubble passes by and is emptied again when a liquid slug passes by. Shorter gas bubbles and increased gas–liquid frequency have been shown to improve mass transfer rates, where the bubble frequency is the number of slugs per unit length. Complete saturation of the liquid film with gaseous components should be avoided as this would not further contribute to mass transfer. Moreover, shorter liquid slugs have been shown to intensify liquid circulation within the liquid slug, thereby enhancing mixing and liquid renewal. However, a minimum liquid slug length is required to sustain stable recirculation patterns and prevent the reduction of convective transport.

The liquid film along the channel wall is therefore relevant and has been measured in several studies (summarized by Haase et al., 2016) which demonstrate that the liquid film thickness is mainly determined by the channel diameter and the capillary number. All equations developed indicate that the liquid film thickness increases if the bubble velocity increases, leading to an enhanced mass transfer. The flow orientation (up- or down-flow) may be important as the influence of gravity has been shown to become relevant for larger channels and square channels.

## 5 Capillary reactors

Capillary gas–liquid contactors are structures of small parallel straight channels (round, square, or triangular channels) separated by a thin wall. The channels can be several millimeters (mm) in diameter (macro-channels), less than 1 mm in diameter (mini-channels), or less than 0.1 mm in diameter (micro-channels). Capillary reactors have gained interest for process intensification over recent decades due to their enhanced mass transfer and improved reaction kinetics (Peng et al., 2022; Haase et al., 2016). The application of capillary channel microreactors to intensify chemical and biocatalytic processes has increased significantly, especially due to rapid progress in the integration of microfluidic devices and miniaturization technology. For instance, there are many areas of study and application where back-mixing is not desired, including the continuous manufacture of fine chemicals and pharmaceuticals, microdevices (e.g., lab-on-a-chip applications), and compact heat exchangers (e.g., printed circuit cooling systems). Several studies have shown that the use of capillary reactors results in higher productivities and a very significant reduction in reactor size for specified chemical and enzymatic processes, as reviewed by Gupta et al. (2010), Haase et al. (2016), and Bolivar and Nidetzky (2013).

## 6 Capillary gas–liquid bioreactor studies

In the last two decades, there have been several proof-of-concept studies demonstrating the feasibility and potential of capillary gas bioreactors containing suspended cell cultures (Table 1). The objectives of these studies have ranged from the removal of volatile organic compounds (VOCs) from indoor air and the abatement of dilute methane emissions to the bioconversion of methane into biopolymers (a sustainable substitute of fossil-based plastics) or high-value products such as osmolytes used in the cosmetics industry. Mass transfer coefficients ( $K_{1a}$ ) in capillary bioreactors may be between one or two orders of magnitude higher than existing biological gas-phase reactors, which would provide a significantly higher improvement than recent proposals to increase mass transfer (Soreanu and Dumont, 2020; Kraakman et al., 2025b).

A single capillary channel as well as a multi-channel set-up, including monolith packings, have been used to create a capillary bioreactor. Several studies have implemented internal gas recycling strategies to enable the decoupling of the optimal conditions for mass transfer in the capillary channels from the gas contact time. A wide range of gas-to-liquid (G/L) ratios have been investigated, which confirmed that this parameter has a limited effect on mass transfer performance (Kreutzer et al., 2005a). Nevertheless, the G/L ratio remains important from an energy-efficiency perspective at large gas flow rates and is best maintained just above the maximum value required to ensure a stable segmented flow pattern.

The addition of non-aqueous liquids (silicone oil and/or surfactants) has proven beneficial in several studies for further overcoming the mass transfer limitations of highly hydrophobic compounds or to provide a buffer to improve stability of the biodegradation process. Some studies have evaluated the long-

TABLE 1 Examples of studies on capillary gas–liquid bioreactors using macro-channels ( $\geq 1$  mm ID) containing suspended cell cultures<sup>a</sup>.

Capillary reactor	Objective	Operating condition	Synopsis of main results	References
Honeycomb monolith (50 cps)	Treatment of high concentration accumulating biomass	Liquid recirculated over a 0.1 m ID $\times$ 0.5 m height monolith column with 3 mm square channels	Fast growing biomass on channel walls, which was controlled simply by frequent rinsing	Kreutzer et al., 2005b; Ebrahimi et al., 2006
Honeycomb monolith (26 $\times$ 26 channels)	Treatment of toluene-polluted air	0.1 m $\times$ 0.1 m $\times$ 0.15 m high monolith column with 3 mm square channels G/L ratio $\sim$ 18–110 Toluene inlet: 0–452 mg m <sup>-3</sup>	Toluene EC up to 32 g m <sup>-3</sup> h <sup>-1</sup>	Jin et al. (2009)
1 acryl channel (3 mm ID, 1 m long)	Methane removal	G/L ratio $\sim$ 0.6–1.5 Methane inlet: 4.5% v/v. Slug contact time: 1.9–3.3 s	Methane removal up to $\sim$ 100 g m <sup>-3</sup> h <sup>-1</sup> K <sub>L</sub> a up to 1.9 s <sup>-1</sup>	Rocha-Rios et al. (2013)
19 glass channels (1 mm ID, 0.1 m long)	Toluene removal	G/L ratio $\sim$ 1 Toluene inlet: 1.5–5.5 g m <sup>-3</sup> Slug contact time: 0.3–2.3 s	Capillary reactor had 13–17 $\times$ greater K <sub>L</sub> a than the conventional bioreactors Toluene EC up to 3,050 g m <sup>-3</sup> h <sup>-1</sup>	Lopez De Leon et al. (2019)
25 glass channels (1 mm ID, 0.1 m long)	Removal of VOCs	G/L ratio $\sim$ 1 Toluene inlet: 1.5–5.5 g m <sup>-3</sup> Slug contact time: 0.3–2.3 s	Sustained treatment over extended periods of time with toluene. ECs of 4,000–9,000 g m <sup>-3</sup> h <sup>-1</sup> K <sub>L</sub> a up to $\sim$ 850 h <sup>-1</sup>	Lopez De Leon et al. (2020)
25 glass channels (3 mm ID, 1.5 m long)	Dilute methane bioconversion to poly (3-hydroxybutyrate)	G/L ratio: 0.1–0.5 Methane inlet: 4% v/v. Gas contact time: 6.7–60 min	Methane bioconversion 63% Yield of 19.8 mg-PHB g-CH <sub>4</sub> <sup>-1</sup>	Cattaneo et al. (2022)
25 glass channels (2.4 mm ID, 1.5 m long)	Removal of VOCs from indoor air	G/L ratio $\sim$ 1.7 Toluene, $\alpha$ -pinene and hexane inlet: $<10$ mg m <sup>-3</sup> With and without silicone oil Gas contact time: 0.7 s	Toluene, $\alpha$ -pinene, and hexane removal in the capillary bioreactor up to 99%, 98%, and 55% K <sub>L</sub> a up to $\sim$ 460 h <sup>-1</sup>	Kraakman et al., 2023, Kraakman et al., 2024
25 glass channels (3 mm ID, 1.5 m long)	Dilute methane bioconversion to ectoines	G/L ratio $\sim$ 1.1 Methane inlet $\leq$ 5% v/v Gas contact time: 30–240 min	Methane bioconversion up to 90%	Herrero-Lobo et al., 2024, Herrero-Lobo et al., 2025
25 channels (1.7 mm PTFE and 2.4 mm glass ID, 1.0 m long)	Dilute methane removal	G/L ratio $\sim$ 0.4–2.5 Methane inlet $\leq$ 5% v/v. Gas contact time: 7.5–33 s With and without the addition of surfactant and/or silicone oil	Methane EC $>$ 200 g m <sup>-3</sup> h <sup>-1</sup> with a RE of $\sim$ 50% at gas contact time of 23 s applying an optimized liquid phase	Kraakman et al., 2025a, Kraakman et al., 2025b

<sup>a</sup>ID, internal diameter; cps, channels per square inch; VOC, volatile organic compound; G/L ratio, gas-to-liquid ratio; v/v, volume per volume; RE, removal efficiency; EC, elimination capacity; K<sub>L</sub>a, mass transfer coefficient.

term operation as well as the quantification of system robustness under typical upset conditions and the characterization of the microbial community.

## 7 Future perspective

Capillary gas–liquid bioreactors have been shown to be effective gaseous treatment systems, as their biological process may benefit from the superior mass transfer rates and low pressure drop. They are therefore promising for environmental applications (such as air quality control, dilute methane abatement, and gas-phase biorefineries). Further studies on capillary gas–liquid bioreactors would be required to fully understand the operating conditions of the treatment of hydrophobic gaseous compounds, especially in terms of input requirements (e.g., energy), scaling up, and aspects relevant for long-term reliable performance—important factors affecting the ultimate cost-effectiveness and acceptance of most applications.

Capillary reactors have been extensively investigated within the context of chemical reaction engineering and as such are

increasingly being used in industrial processes due to their unique hydrodynamic characteristics. Most research on applications of capillary reactors are based on mini- and micro-capillary channels ( $d < 1$  mm). Capillary bioreactors with suspended biomass may require larger capillary channels ( $>1$  mm) as they need to generate the conditions to prevent blockages of the capillary channels. Although some capillary bioreactor studies have shown that removing biomass is easy by simply by rinsing with water (Kreutzer et al., 2005b), the shear stress inside the channels may be sufficiently high to prevent biomass growth on the inner walls of the capillary channels. Several long-term experiments with capillary gas bioreactors have shown that channel blockage can easily be prevented when the channel diameter is large enough. Fortunately, channel diameter has been shown to barely influence mass transfer under segmented flow conditions (Kreutzer et al., 2005a; Bordel et al., 2024). Furthermore, the pulsating shear stress created by the segmented gas–liquid bubble-train flow likely contributes to limiting biomass adhesion, as shown in several long-term studies, without negatively affecting microbial activity (Kraakman et al., 2025b).

Although several examples have demonstrated improved overall bioreaction efficiency at lab-scale treating relatively small air volumes, only a limited number of capillary bioprocesses have been applied in industry, likely due to the challenge of maintaining a uniform flow distribution across the capillary channels as their number increases. Different scale-up approaches for gas–liquid and liquid–liquid capillary reactors have been discussed in the literature to address issues in terms of device design, cost, and reactor size (Dong et al., 2021). Fundamental knowledge of the hydrodynamics inside channels is thus essential for reactor design. Future research into capillary gas–liquid bioreactors aimed at improving air quality and enhancing the economic viability of gas-phase biorefineries should prioritize systems employing macro-channels (1–4 mm) and focus on the following key aspects.

- Further systematic evaluation of the key parameters that are interdependent and somewhat specific for different gaseous streams and overall treatment objectives. This involves gas–liquid segmented flow stability, gas–liquid maximal mass transfer, and overall system pressure loss.
- The proper distribution approach to mix the gas and liquid at the inlet side of the multiple capillary channels to form the gas–liquid bubble train, as no redistribution can occur once inside the channels. An improved understanding of gas–liquid mixing methods could help to better control the bubble frequency per unit length and minimize the gas and liquid hydraulic residence time distribution among multiple channels. Empirical correlations are used to predict the length of the liquid slug and gas bubble in single channels but may not be applicable to multi-channel capillary reactors. Creating relatively short gas bubbles and liquid slugs would be generally beneficial as this improves mass transfer and increases flow pattern stability, while their sizes need to be adjustable to optimize performance for target compounds and for meeting specific objectives.
- The influence of the channel wall material, particularly differences in surface roughness and wettability parameters, may also play a significant role and should be further investigated.

Nevertheless, there is a need to upscale macro-channel bioreactors to evaluate their efficiency and establish them as a viable option. In this context, a 1 m<sup>3</sup> multi-capillary bioreactor is being scaled-up in the European project CHEERS, which is devoted to the conversion of biogas into the high-value-added product ectoine.

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NK: Writing – original draft, Writing – review and editing. AT: Writing – review and editing. BS: Writing – review and editing. SB: Writing – review and editing. RL: Writing – review and editing. RM: Supervision, Validation, Project administration, Writing – review and editing, Resources, Funding acquisition.

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Author NK was employed by Jacobs.

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