Ministero dell'Università e della Ricerca

FIS

POLITECNICO MILANO 1863 | DEPARTMENT OF ENERGY

Ionic Liquids for CO_2 Capture

Technological Review Focused on Bubble Columns

03.09.2026 | Alberto Arici

AURIGA project – The goals

AURIGA - Unveiling the RIddles of GAs-liquid fluid dynamics

Towards novel carbon dioxide absorption systems

General Goals

Formulate a **novel theory** to unveil some of the riddles (e.g., multi-scale connections) of **gas-liquid fluid dynamics** and apply the acquired perspective to develop a novel **ionic-liquid reactor** to absorb **carbon dioxide** from sour gas streams.

Specific Goals

1. Develop a **physical-based approach** to describe a-priori the flow patterns in **bubble columns**, including the relationships between local and global flow properties;
2. Set-up **experimental facilities** (small-scale and large-scale) to study the influence of **ionic liquids** on the local and the global fluid dynamics and to study the mass transfer in ***CO_2-IL* systems**;
3. Scaling-up towards the industrial scale.

AURIGA project – The Team

Principal Investigator
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Post Docs

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Stefano Puricelli

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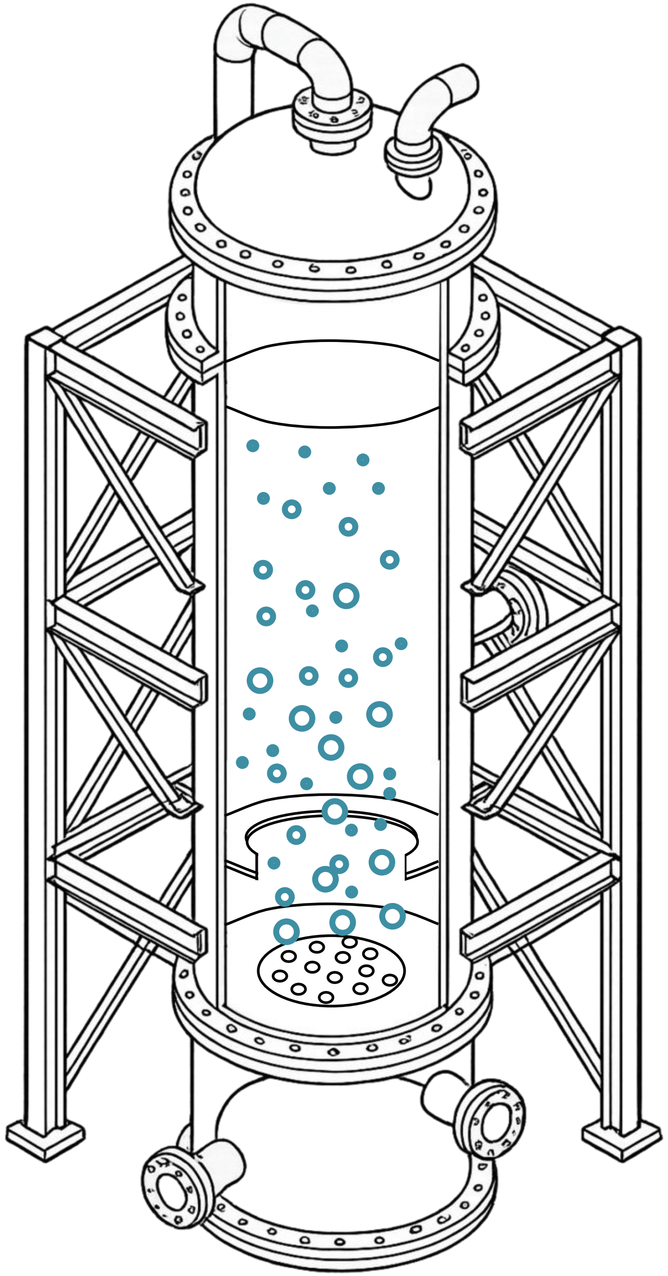
Francesco Pierini

Motivation & Aim

CO_2 emissions are a major climate challenge, requiring scalable capture solutions

Chemical absorption is the most mature technology for industrial CO_2 capture

Large scale **gas-liquid processes** are widely used technologies



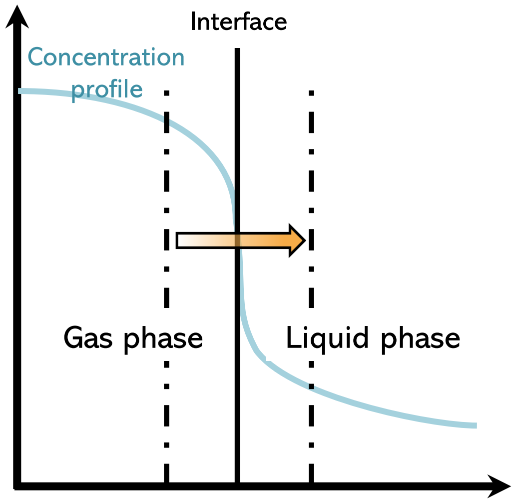
Among gas liquid-contactors **bubble columns** are of particular interest

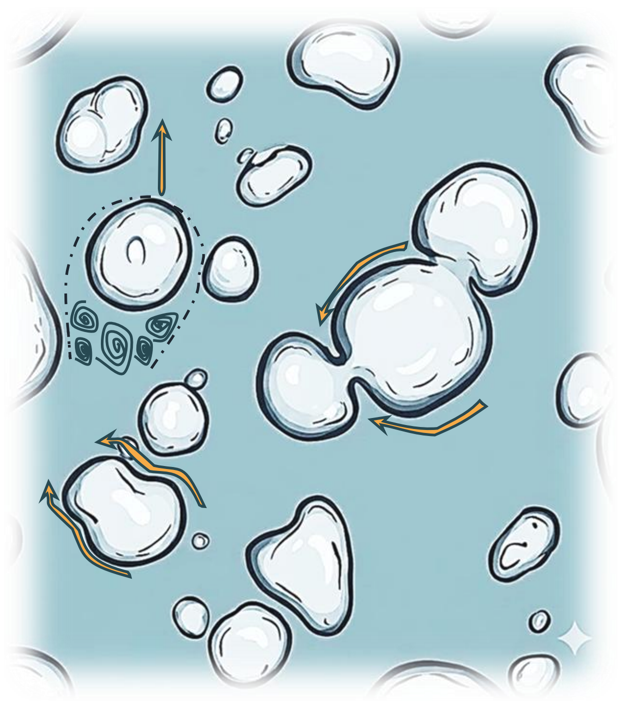
Conventional amine systems are effective but suffer from several **drawbacks**

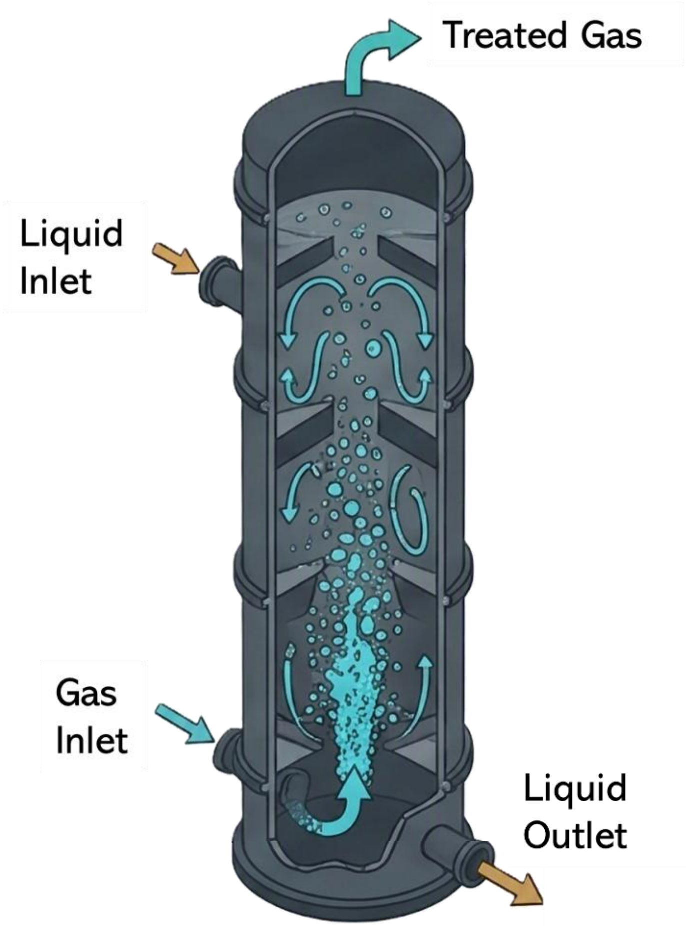
Ionic liquids have emerged as promising alternative

[1] Nunes (2023), Enviroments
[2] Rochelle (2009), Science
[3] Hospital-benito et al. (2020), Chemical Engineering Journal

CO_2 Absorption: a multiscale problem







CO_2 solubility, diffusivity and chemical reaction

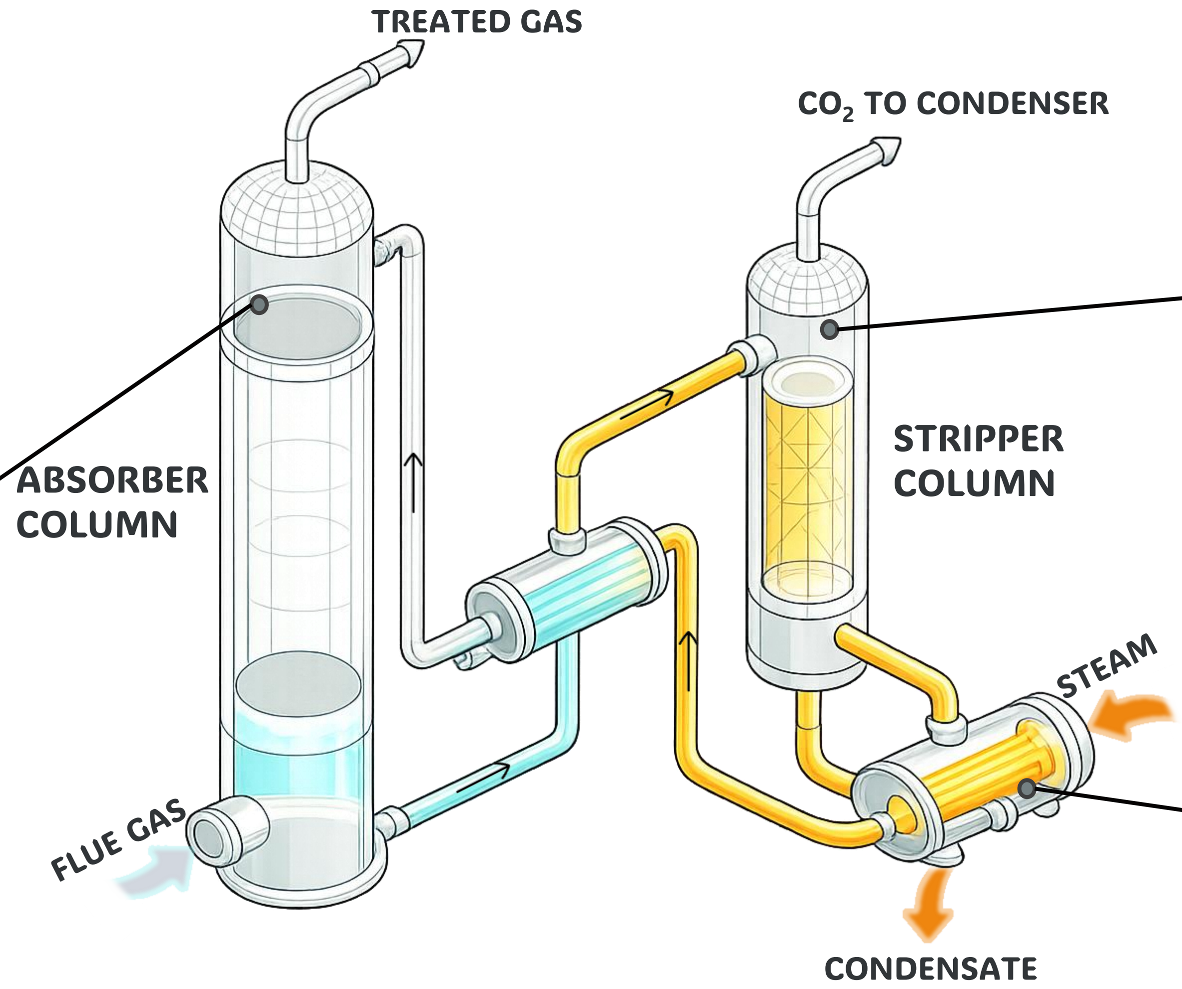
Liquid-film resistance, bubble size and interface renewal

Gas distribution, flow regime and $k_L a$

Solvent properties affect reactor performance through coupled **molecular**, **interfacial** and **hydrodynamic mechanisms**.

[4] Besagni et al. (2018), ChemEngineering
[5] Zhang et al. (2014), AIChe Journal

The Baseline: Why move past Amines?



Volatility

Evaporative **solvent losses** require solvent make-up and additional emission-control sections.

Degradation

Oxidative and thermal degradation creates **highly toxic byproducts**

Energy penalty

Solvent regeneration requires massive **heat** reducing the net power plant output

[2] Rochelle (2009), Science
[6] Haszeldine (2009), Science

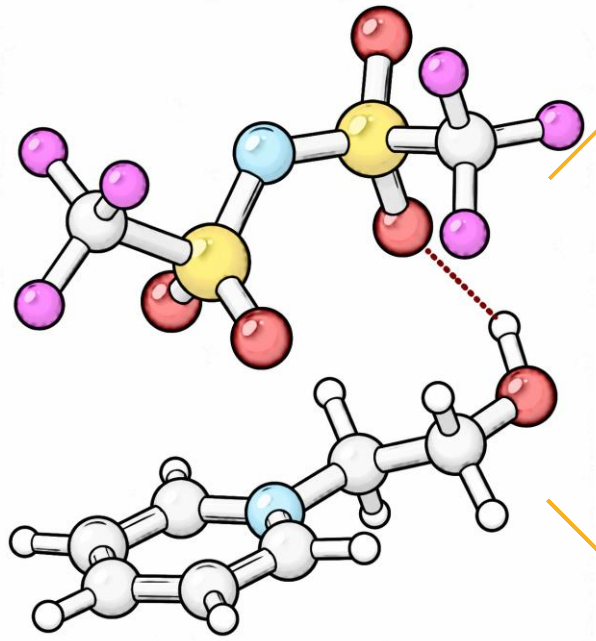
The Ionic Liquid Promise

Infinite Tunability

Over **10^{14} possible cation/anion combinations** allow precision engineering of viscosity, capacity and thermal properties

High stability

High thermal and chemical endurance allows for alternative **high-efficiency regeneration** strategies like flash desorption



Zero vapor pressure

ILs do not evaporate eliminating **solvent losses** and atmospheric emission entirely

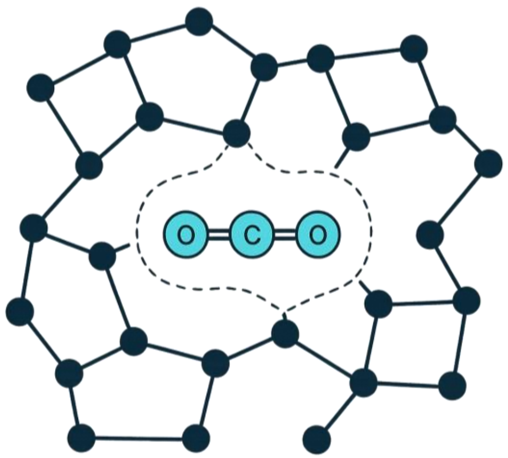
Selective affinity

Exceptional physical and chemical **affinity for CO_2** over a lot of other gases

[3] Hospital-benito et al. (2020), Chemical Engineering Journal
[7] Chiappe et al. (2005), Journal or Physical Organic Chemistry
[8] Wasserscheid et al (2002)

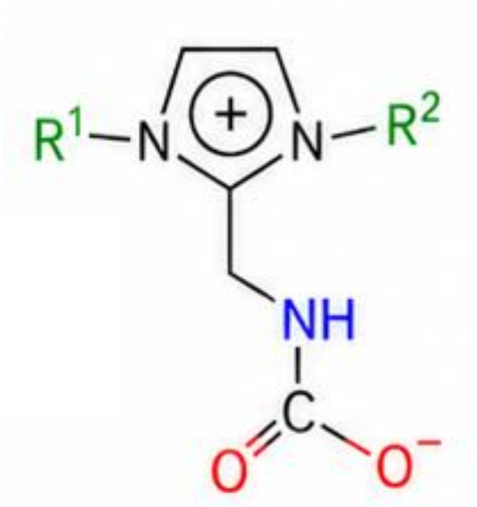
Absorption Mechanism

Physical absorption (RTILs)



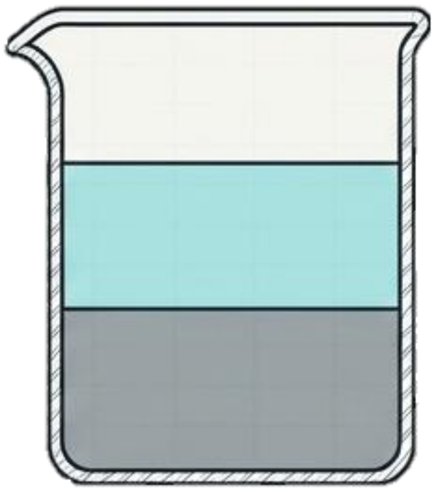
CO_2 dissolves physically via **Van der Waals** forces.
Low capacity but extremely **easy to regenerate**

Chemical absorption (TSILs)



CO_2 react chemically with either the cation, anion or both. Large **uptake** but increase the viscosity.

Phase change absorption (PCILs/RILs)



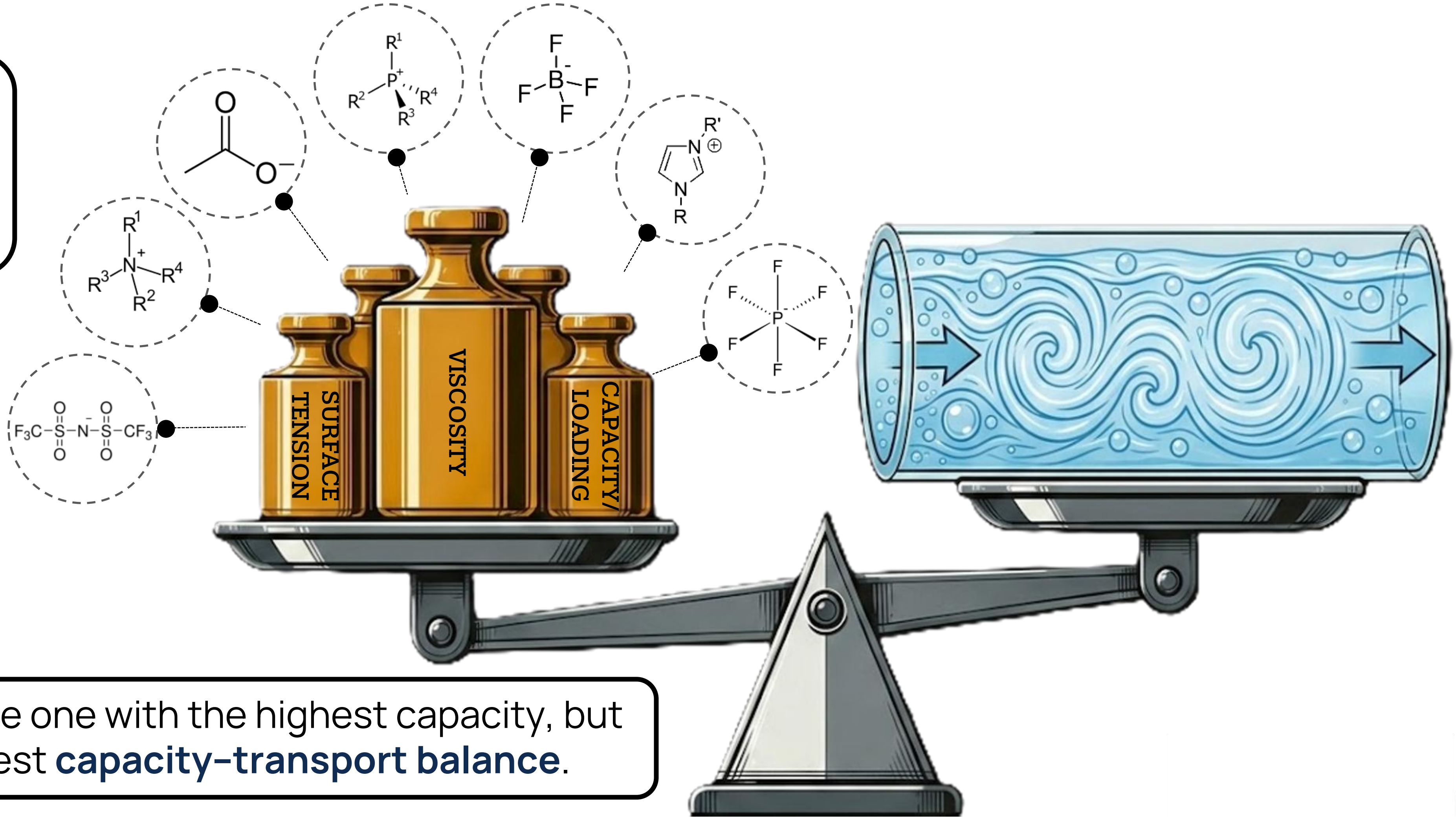
CO_2 triggers a liquid-solid or liquid-liquid **phase transition** allowing the separation of a CO_2-rich phase.

[9] Zhao et al. (2025), Chem soc rev
[10] Muldoon et al. (2007), J Phys Chem
[11] Gurkan et al. (2010), J Am Chem Soc

The thermodynamic-transport trade off

Functionalization can increase CO_2 affinity, selectivity and loading capacity.

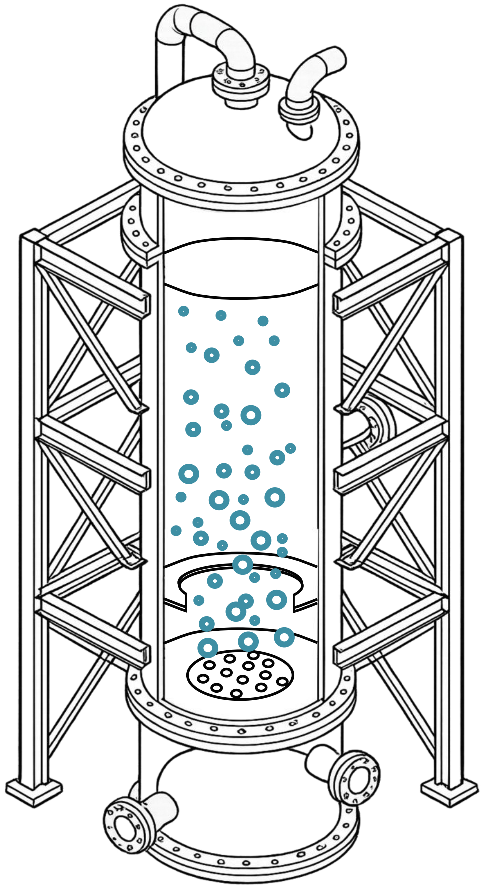
Stronger ionic association and CO_2 binding increase **viscosity** (200 mPa·s).



The best solvent is not the one with the highest capacity, but the one offering the best **capacity–transport balance**.

[3] Hospital-benito et al. (2020), Chemical Engineering Journal
[12] Gurkan et al. (2010), J Phys Chem

Why bubble columns for IL-based CO_2 capture



1 Reactor advantage
Simple construction, low maintenance and high gas–liquid contacting make bubble columns attractive for CO_2 absorption.

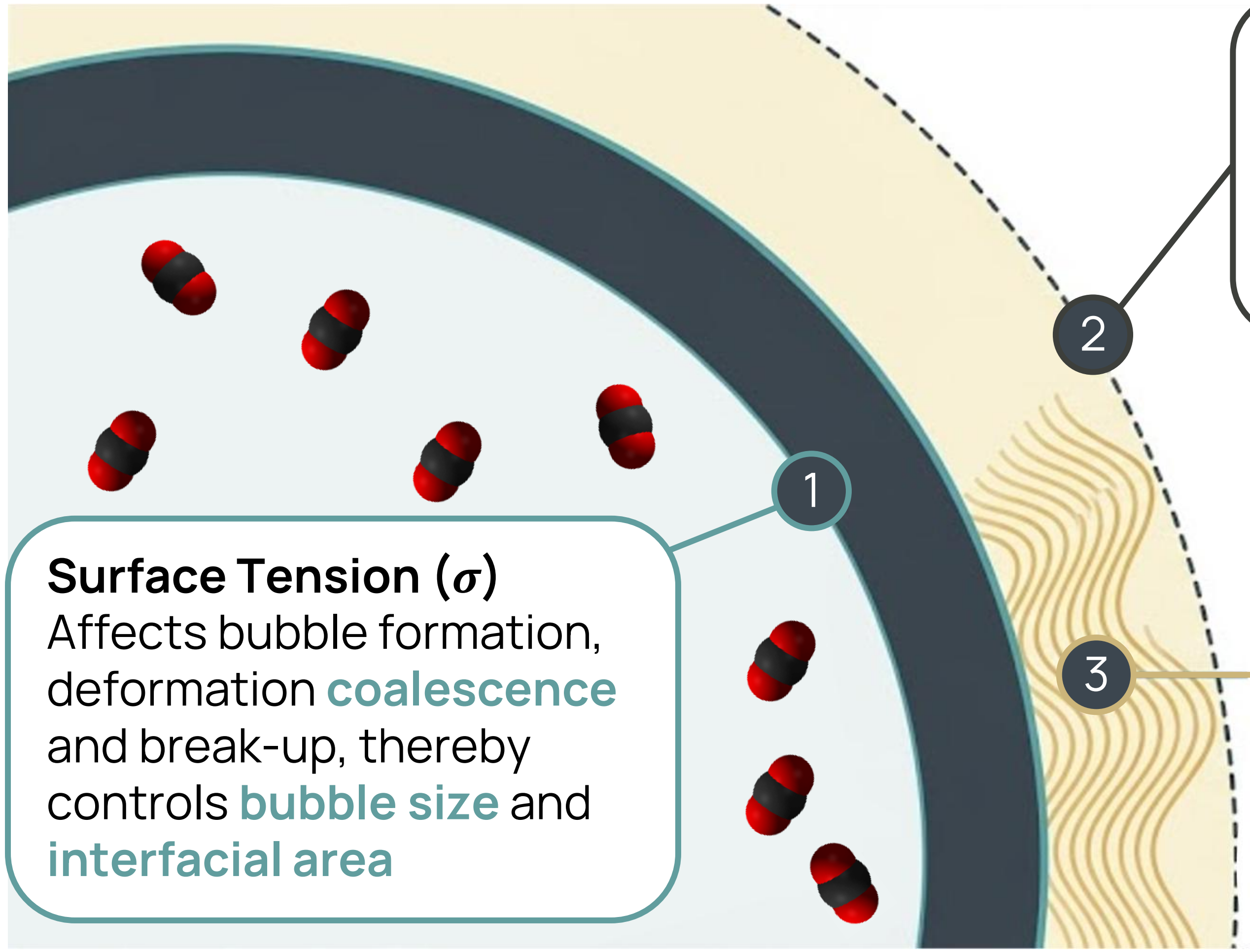
2 Performance variables
Gas holdup, bubble-size distribution, flow regime and interfacial area determine the effective kLa.

3 Scale-up sensitivity
Sparger design, column diameter and flow-regime transitions strongly affect hydrodynamics and mass transfer.

4 IL-specific penalty
High IL viscosity and interfacial effects can shift regimes, enlarge bubbles, reduce gas distribution and lower kLa.

[4] Besagni et al. (2018), ChemEngineering
[13] Abro et al. (2021), Chemical Engineering Science

How liquid properties controls CO_2 mass transfer



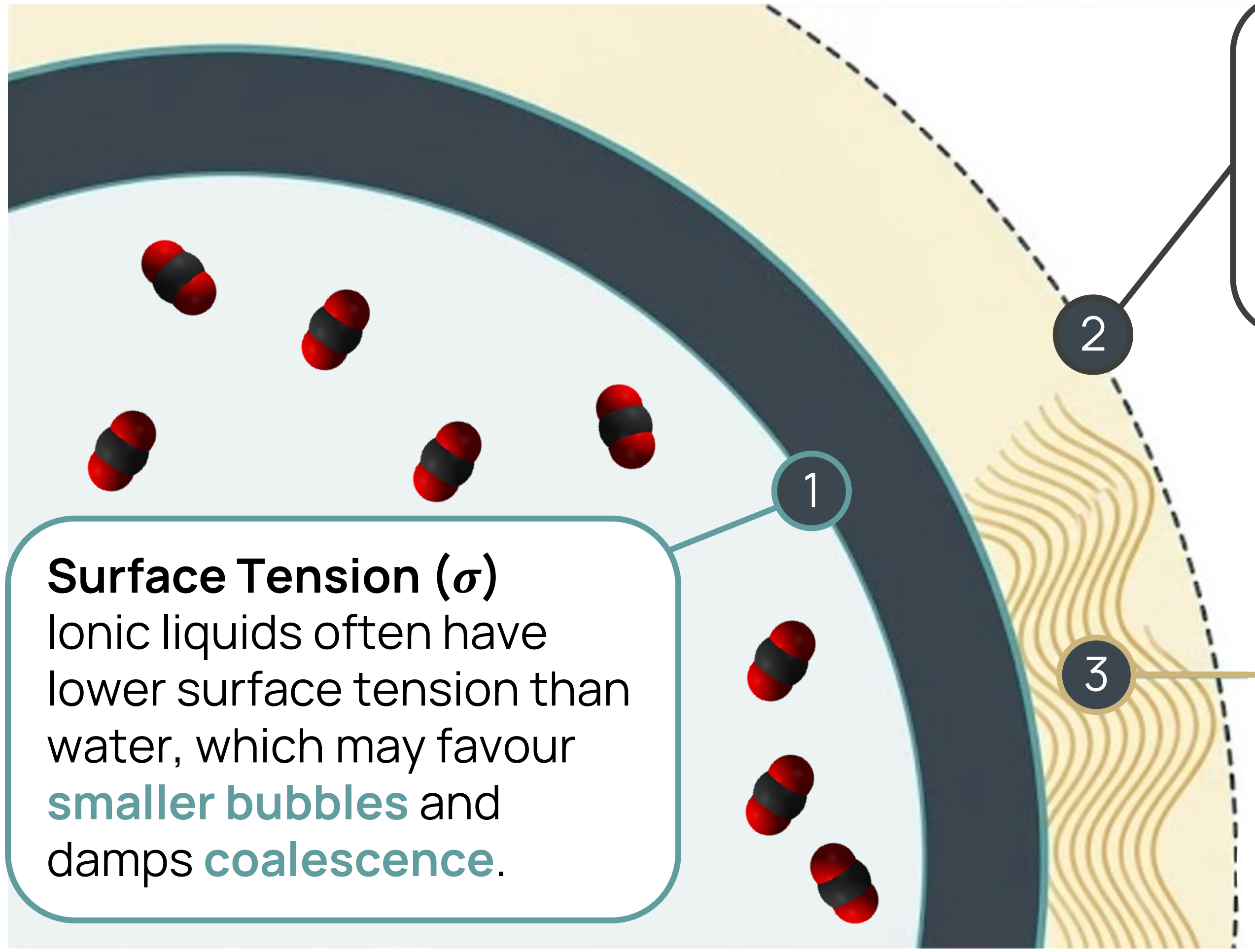
Viscosity (η)
High viscosity reduces **diffusivity**, damps **turbulence** and bubble break up, increasing film resistance

Surface Tension (σ)
Affects bubble formation, deformation **coalescence** and break-up, thereby controls **bubble size** and **interfacial area**

Reaction kinetics - Hatta Number (*Ha*)
Reaction kinetics influence the **chemical enhancement** and CO_2 absorption flux, until the process become limited by **diffusion** or **reactant availability**

[14] Besagni et al. (2017), Chemical Engineering Science
[15] Kovats et al. (2022), SSRN Journal

How liquid properties controls CO_2 mass transfer



Viscosity (η)
Neat ILs typically show viscosities of **50–150 mPa·s**. This reduces CO_2 **diffusivity** and **interfacial area** promoting larger bubbles .

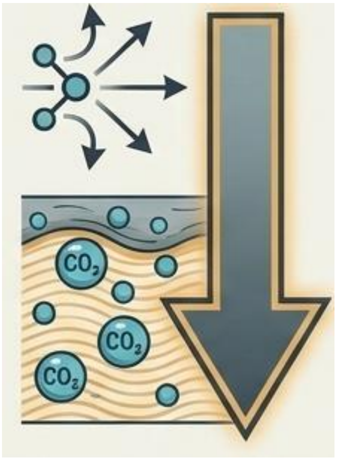
Surface Tension (σ)
Ionic liquids often have lower surface tension than water, which may favour **smaller bubbles** and damps **coalescence**.

Reaction kinetics - Hatta Number (*Ha*)
Conventional ILs rely on **physical absorption** and show limited chemical enhancement. TIL s can operate at **high Ha**, increasing the absorption flux.

[14] Besagni et al. (2017), Chemical Engineering Science
[15] Kovats et al. (2022), SSRN Journal

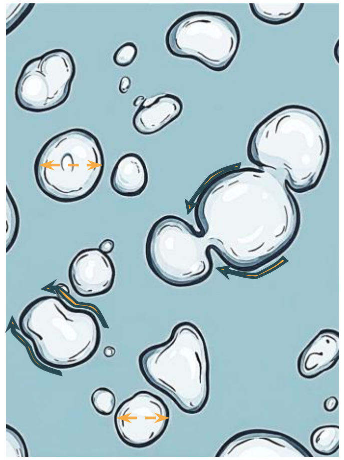
Deconstructing kLa in ionic-liquid systems

$$k_L \cdot a$$



Damping effect
High viscosity of ILs lowers CO_2 diffusivity and slows liquid-film renewal, reducing the physical kL.

Enhancing effect
In reactive ILs, fast CO_2 binding maintains a strong concentration gradient within the liquid film increasing the absorption flux and partly compensate for the low kL.



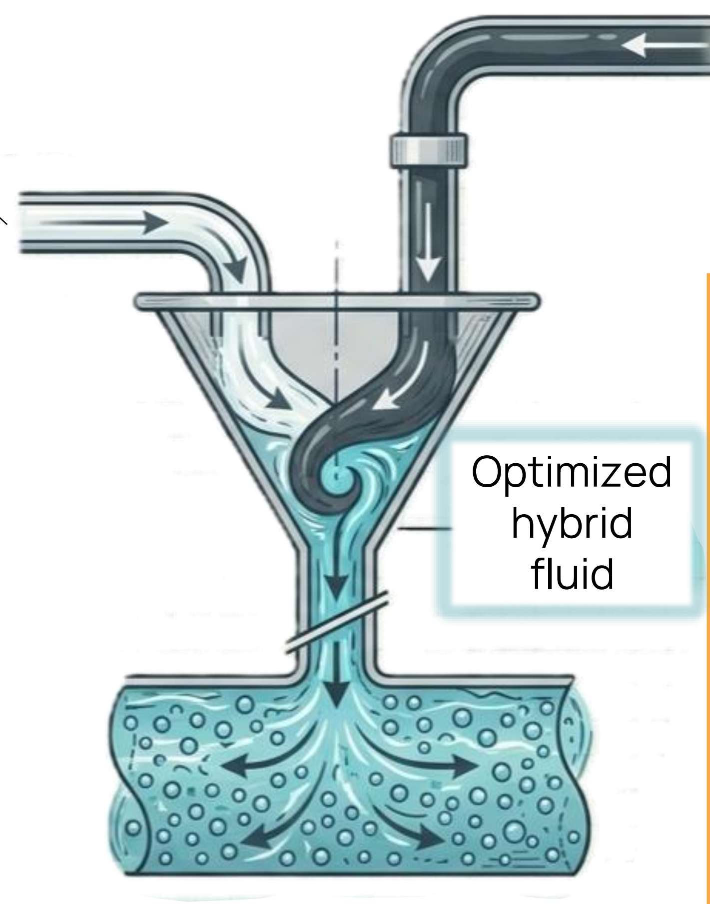
Damping effect
High viscosity suppresses bubble breakup and favors larger bubbles

Enhancing effect
The relatively low surface tension and reduced interfacial mobility of IL systems can limit coalescence, creating larger population of separate bubbles.

Conclusion: Net kLa results from competing transport, reaction and interfacial effects.

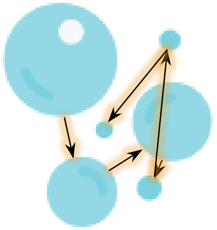
[16] Shiflett et al (2005), Ind Eng Chem Res
[17] Ali et al. (2018) Chemical Engineering Research and design

The pragmatic route: hybrid solvent systems



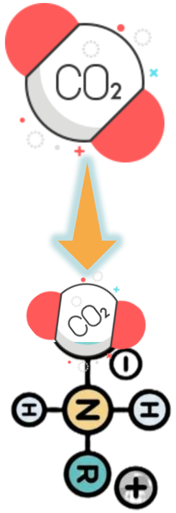
Physical transport wins!

Adding a co-solvent sharply reduces **viscosity**, increasing CO2 **diffusivity** and interfacial area.



For [BMIM][BF_4]-methanol mixtures,the Sauter mean bubble diameter decreasesfrom approximately 7 mm to 4 mm.

Chemical absorption wins!



Blending ILs with reactive solvents such as amines introduces **chemical enhancement**, increasing both the **CO_2 absorption** flux and the total loading capacity.

Takeaway: Hybrid IL systems are more promising than neat ILs for practical CO_2 capture.

[13] Abro et al. (2021), Chemical Engineering Science
[18] Guo et al. (2018), Chemical Engineering and Processing

Industrial Viability

OPEX & System advantages

- Lower regeneration duty and potentially simpler **solvent recovery**
- No solvent evaporation and reduced **make-up requirements**
- No water-wash section, reducing **water use** and cooling demand
- Bubble columns offer **simple construction**, no moving internals and low maintenance

Selected studies simulations report **energy savings of about 30%** compared with MEA.

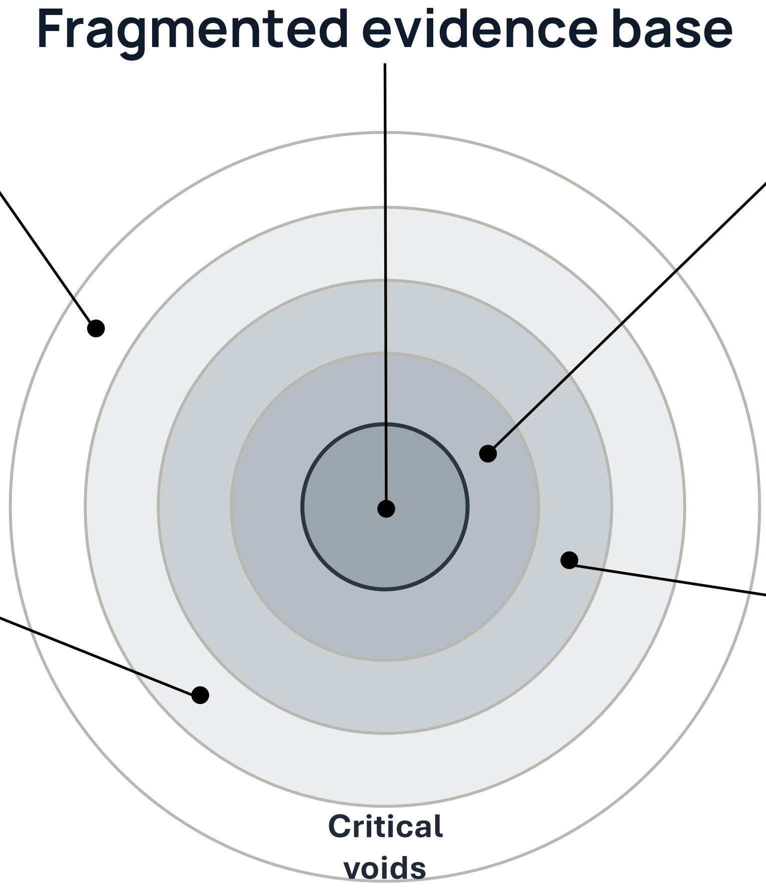
CAPEX & System Challenges

- **Larger absorbers** due to low kLa
- High initial **solvent** inventory **cost**
- Possible higher **pumping** requirements
- Uncertain **toxicity** and biodegradability
- **Limited** long-term **stability** and scale-up data

Process savings are promising, but not yet sufficient to guarantee lower total capture cost.

[3] Hospital-benito et al. (2020), Chemical Engineering Journal
[19] Ma et al. (2023), International Journal of Greenhouse Gas Control
[20] Valencia-Marquez et al. (2015), Ind Eng Chem Res

Research Gaps



1 CO_2-loaded properties

η, D_{CO_2}, σ and ρ are rarely measured together as functions of CO_2 loading, temperature and pressure

2 High-pressure hydrodynamics

High-pressure solubility data exist, but pressurized bubble-column measurements of holdup, bubble size and mass transfer are scarce.

Long-term stability 3

Continuous-cycle performance under water, O_2, SO_x, NO_x and particulate exposure remains poorly documented.

Consistent benchmarking 4

Few ILs are compared under identical reactor and operating conditions, limiting scale-up and model validation.

Takeaway: the key gap is not the absence of data, but the absence of integrated and comparable datasets.

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Thank you for the attention!

Acknowledgment

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Contatti

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