Polymeric Materials for High-Pressure CO_2 Transport: Enabling a Sustainable, Reliable and Durable CCS Value Chain

The continuous increase in greenhouse gas emissions, primarily carbon dioxide (CO_2), has accelerated global warming and reinforced the urgency of implementing effective mitigation strategies. Among the technologies currently available, Carbon Capture, Utilization and Storage (CCUS) is widely recognized as one of the most effective short- to medium-term solutions for reducing emissions from hard-to-abate industrial sectors while supporting the transition towards climate neutrality (Mitchell, 1989; U.S. Global Change Research Program, 2018). Today, anthropogenic activities release more than 36 billion tonnes of CO_2 annually, together with significant emissions of methane and nitrous oxide, making the deployment of reliable CCUS technologies a strategic priority for achieving the Net Zero targets (Ansaloni et al., 2020).

Polymeric materials, in this concern, offer a promising and efficient alternative to energy-intense traditional gas separation, transport, and sequestration methods to limit environmental disaster, such as global warming and climate change, and to improve engineering industrial processes.

Dense polymers can play a relevant role as they can serve as membrane materials for gas separations or layers for fluid transport, rather than protective liners and sealants for dense phase systems in the transport value chain. The goal was to provide a more accurate picture of polymer performances in realistic industrial conditions, both concerning gas separation and capture, and system for fluid transport and storing.

In this concern, the transport of captured CO_2 under high-pressure conditions is one of the major challenges of CCS value chain as the long-term reliability of non-metallic components represents a critical requirement for pipeline safety and operational integrity. Polymeric sealing materials, including both thermoplastics (such as PTFE, PVDF, PEEK…) and elastomers (i.e. EPDM, HNBR and FKM), are extensively employed in pipeline systems, sealings, valves and compressors, where prolonged exposure to dense or supercritical CO_2 may induce sorption, swelling, plasticization and diffusion phenomena that significantly affect their mechanical performance. Moreover, an integrated experimental and modeling approach is employed to characterize the thermodynamic and transport behaviour of CO_2 in commercial elastomers over a wide range of pressures and temperatures, thereby overcoming the experimental limits. Lattice Fluid and Non-Equilibrium Lattice Fluid models allowed to describe CO_2 gas sorption in commercial rubbery and glassy polymers employed in Carbon Transport scenario (down to - 50°C and at pressure up to 100 bar), while the Standard Transport Model (STM) has proved to be very reliable in the description of gas permeability behavior. The model results, function of the kinetic mobility coefficient and the thermodynamic factor, were validated against experimental data available and used predictively to gather information on the solubility behavior of the penetrant and the changes in the diffusion coefficient with concentration. That allows to comprehend the penetrant-polymer interaction, together with the effect of dense phase CO_2 on polymer-based materials, as well as to predict the molecular behavior of these polymers in cryogenics environments, allowing the correlation of material composition, transport properties and failure mechanisms (Ghiara et al., 2025; Signorini et al., 2023).

Overall, the activities carried out at the University of Bologna demonstrate how polymer science can contribute across multiple stages of the CCUS value chain, from the selective separation of CO_2 to the qualification of materials for its safe transportation. By integrating membrane engineering, transport modelling and materials characterization, this research provides the scientific basis for the development of more efficient, reliable and sustainable carbon management technologies,

contributing to the implementation of next-generation CCUS infrastructures and supporting the transition towards a climate-neutral energy system.