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RESEARCH THESIS ON:

DOMAIN ADAPTATION FOR VIRTUAL SENSING IN CARBON CAPTURE AND STORAGE: COMBINING SIMULATED AND FIELD DATA

CONTEXT OF THE RESEARCH

Carbon capture and storage (CCS) will play a critical role in future decarbonization efforts to meet the Paris Agreement targets and mitigate the effects of climate change. The process typically involves CO_2 flow from a compression station to the injection wells through a network system and its safe storage into a depleted oil and gas reservoir. In this context, real-time well monitoring of the process relies on continuous bottom-hole measurements of pressure and temperature. However, physical sensors may fail, requiring bottomhole maintenance interventions, which are costly and dangerous. Virtual Sensors (VS) offer a powerful solution by estimating bottomhole critical variables from other available measurements, enabling on one hand to assess the health state of physical sensors, and, on the other hand, bottomhole monitoring even in case of physical sensors failure.

An Artificial Intelligence (AI)-based Virtual Sensor for Carbon Capture and Storage (CCS) operations has already been developed from field data [1]. However, field measurements are limited and cover only a narrow range of operating conditions. As a consequence, the resulting VS may underperform when different operating conditions arise. Additionally, in the early operation of the well the amount of field data is not sufficient to develop the VS, causing its delayed deployment. An opportunity for increasing VS generalization capability and anticipate its deployment comes from data generated by a physics-based simulator of the well, which can span a wider range of operating conditions and can increase the amount of data during early operations. However, training the VS on the merged simulated and field data is challenging for two reasons. First, during the initial operation of a well, the few available field data are largely outnumbered by the simulated data, which biases the VS towards the simulated domain and reduces its accuracy on the field data. Second, the distributions of simulated and field data inherently differ due to noise, modeling errors and operational drifts, and a simple merge does not address this domain shift. Domain adaptation, which aims at transferring the knowledge learned in a source domain (the simulated data) to a different but related target domain (the field data), offers a promising way to leverage the information in both types of data without merging them in a single training set.

OBJECTIVES OF THE RESEARCH

In this context, the final objective of the thesis is to develop and validate an AI-based VS for CCS applications, based on domain adaptation to optimally exploit the information content of simulated and field data. The thesis work will build on the VS previously developed for the estimation of bottomhole critical quantities in CO_2 injection wells [1]. The thesis will be structured into the following phases:

- *Literature Review:* Analysis of AI-based VS for CCS and Oil & Gas, with focus on domain adaptation and transfer learning methods for combining simulated and field data;
- *Exploratory Data Analysis:* Analysis of real and simulated data from a real case study, with focus on the differences between their distributions;
- *Method Development:* Development of methods with documented Python code for estimating bottomhole critical quantities by domain adaptation (e.g., fine-tuning, feature alignment, adversarial learning or other transfer learning techniques);
- *Validation:* Final validation on the real case study, and benchmarking against VSs trained using only simulated data, only field data or a mixture of the two.

The thesis work will be carried out within the ENI-Politecnico di Milano (LASAR³) collaboration on virtual sensing for CCS. Field and simulated data will be provided along with operational constraints. Periodic technical meetings involving the industrial partner will be organized to review progress and validate results against real world challenges.

Required Skills

Coding skills in Python and good practices.
Technical communication skills in English.
Familiarity with machine learning and deep learning approaches will be appreciated. Knowledge on domain adaptation and CCS processes is a plus.

Research Team

For further information and details about this thesis, please contact:

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- **Prof. Enrico Zio,** enrico.zio@polimi.it

References

[1] E. Vignati, F. Ursini, G. Floreale, P. Baraldi, I. Chouybat, E. Zio. Virtual Sensing for Real-Time Well Monitoring in CCS projects. *World CCUS Conference 2026*, European Association of Geoscientists & Engineers, 2026, pp. 1–5. doi: 10.3997/2214-4609.202622055.