

ALGORITHMIC DEVELOPMENT OF TIME-DEPENDENT PINCH ANALYSIS BASED METHODOLOGY FOR TRANSIENT THERMODYNAMIC OPTIMIZATION IN FAST HYDROGEN REFUELLING

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Abstract

Given the relentless growth of global energy demand across all sectors, adopting sustainable alternatives to conventional sources has become an absolute necessity. This transition toward decarbonized energy matrices relies heavily on the development of optimized methods and technologies, and despite inherent complexities, the use of hydrogen stands out as a prominent alternative in key sectors. However, the commercial and operational viability of hydrogen infrastructure—particularly Hydrogen Refuelling Systems (HRS)—is currently constrained by severe thermodynamic inefficiencies and high parasitic energy demands associated with gas compression, storage, and thermal management. Navigating these highly coupled, non-linear thermal and fluidic phenomena require robust numerical frameworks capable of systemic analysis and optimization.

This investigation presents the development of a novel computational methodology designed to exhaustively analyse the heat recovery potential within complex, transient thermodynamical systems. Methodologically, the framework leverages a lumped-parameter digital twin formulated via Differential-Algebraic Equations (DAEs). To navigate highly dynamic thermal profiles, this study profoundly extends classical steady-state methodologies. Traditional Pinch Analysis is fundamentally limited when applied to transient systems where temperatures and thermal loads fluctuate rapidly. To bridge this gap, this investigation introduces a rigorous Time-Dependent Pinch Analysis methodology. This novel numerical approach allows thermodynamic streams to dynamically change their operational classifications (hot/cold) across discrete time steps, enabling the algorithmic optimization of theoretical heat recovery bounds even in highly variable scenarios. This is comprehensively complemented with Temporal Gradient metrics to mathematically map exergy destruction throughout the transient process.

While the mathematical formulation of this advanced Pinch architecture is fundamentally agnostic and adaptable to broad thermodynamic networks, it is evaluated herein through a highly resolved HRS digital twin. Specifically, the analysis focuses on exploring the direct heat exchange potential with the vehicle's

onboard storage tank during rapid filling protocols. Managing the exothermic heat of compression and inverse Joule-Thomson effect directly at the vehicle receptacle presents severe, non-linear dynamic loads. By isolating this critical subsystem, the study evaluates the theoretical limits of direct thermal recovery strategies required to meet strict temperature regulations. Directly extracted metrics from the algorithm's execution establish precise dynamic heat recovery targets for both specific instantaneous moments and the overall process, projecting a potential heat recovery rate up to 45%, and estimating that optimal thermal integration can offset the reliance on external cooling utilities by up to 33%. Furthermore, the analysis accurately maps the critical temporal zones of exergy destruction, enabling the optimization of ideal temperature ranges for both external and internal fluid streams.