FLEXPRESS® Material-as-a-Service: An Innovative Fluid Thermal Expansion Damping Mechanism - From Materials Science to Digital Transformation

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Introduction

Thermal expansion of working fluids is a major source of pressure fluctuations, mechanical fatigue, reduced reliability, and increased maintenance in closed thermo-hydraulic systems. Conventional expansion vessels mitigate these effects through gas compression; however, their performance is inherently limited by thermodynamic constraints, restricted optimisation potential, and long-term degradation under demanding operating conditions. The **FLEXPRESS** project introduces the **New Thermal Expansion Damping Mechanism (NTEDM)**, an innovative metamaterial based on **entropic elasticity** and a patented vacuum-engineered microstructure. Instead of dissipating expansion energy through gas compression, the NTEDM passively absorbs volumetric expansion via the reversible thermo-mechanical response of elastomeric materials containing engineered microscopic sealed vacuum cavities. This architecture reduces the apparent bulk modulus and thermal conductivity, improving pressure damping, thermo-hydraulic stability, and operational reliability.

The concept is experimentally validated using the **Behaviour of Materials under Variable Thermo-Hydraulic Conditions (BMVTHC)** platform, which provides controlled thermo-hydraulic testing, high-resolution metrology, automated data acquisition, and long-term reliability assessment. Experimental data continuously update **Digital Twin** models integrating **Computational Fluid Dynamics (CFD)**, **Finite Element Analysis (FEA)**, **Machine Learning**, and **Generative Artificial Intelligence**, enabling inverse materials design and continuous optimisation. Beyond technological innovation, FLEXPRESS introduces an **Artificial Intelligence-enabled Material-as-a-Service (MaaS)** concept, transforming advanced metamaterials into intelligent engineering services through Digital Twins, predictive maintenance, and continuous performance optimisation. This multidisciplinary approach establishes a scalable pathway from advanced materials science to digital transformation and sustainable industrial innovation.

Research Methodology

The scientific methodology combines experimental validation with advanced computational modelling in a continuous optimisation cycle.

A dedicated Behaviour of Materials under Variable Thermo-Hydraulic Conditions (BMVTHC) experimental platform has been designed to evaluate material performance under realistic operating conditions. The facility enables controlled testing over temperatures ranging from approximately 5°C to above 300°C, pressures up to 16 bar, and precisely regulated fluid flow using water, glycol mixtures and dielectric fluids. High-resolution instrumentation, automated data acquisition, three-dimensional deformation measurements and long-duration fatigue testing generate high-quality datasets suitable for scientific validation and engineering certification.

Experimental observations continuously update Digital Twin models integrating:

Computational Fluid Dynamics (CFD); Finite Element Analysis (FEA); physics-based constitutive models; thermo-hydraulic simulations. Artificial Intelligence algorithms analyse experimental data, identify relationships between material architecture and performance, and support inverse materials design. The resulting closed-loop methodology follows the sequence: **Material Design → Prototype Manufacturing → Experimental Validation → Digital Twin Updating → AI Optimisation → Material Redesign**

This integrated workflow accelerates innovation while continuously improving prediction accuracy and material performance.

Results and Innovation

FLEXPRESS® is expected to deliver a validated family of NTEDM metamaterials together with a permanent experimental research infrastructure, Digital Twin libraries, Artificial Intelligence optimisation algorithms and engineering databases supporting future industrial applications.

The project's principal scientific innovation lies in replacing conventional gas-compression expansion technology with an advanced metamaterial whose thermo-mechanical response is governed by entropic elasticity. The engineered vacuum microstructure enables pressure damping characteristics not achievable with traditional engineering materials.

An equally important innovation is the introduction of the Material-as-a-Service (MaaS) concept. Instead of commercialising a passive engineering component, FLEXPRESS transforms advanced materials into continuously monitored intelligent engineering services supported by Digital Twins, Artificial Intelligence and predictive maintenance. This service-oriented approach creates recurring value through continuous performance optimisation and lifecycle management while strengthening long-term industrial competitiveness.

Potential application sectors include heat pumps, district heating and cooling networks, HVAC systems, renewable energy technologies, industrial thermal processes, aerospace engineering, medical devices and data-centre cooling. Across these applications, improved pressure stability, reduced maintenance requirements and enhanced energy efficiency provide significant technological and economic benefits.

Concluding Remarks FLEXPRESS introduces an innovative New Thermal Expansion Damping Mechanism (NTEDM) based on advanced metamaterials, Digital Twins, and Artificial Intelligence for intelligent thermo-hydraulic pressure management. The project combines experimental validation through the BMVTHC platform with CFD, FEA, and AI-driven optimisation to accelerate material development and industrial deployment. The proposed Material-as-a-Service (MaaS) concept transforms advanced materials into intelligent engineering services, supporting predictive maintenance and continuous performance optimisation. Collectively, FLEXPRESS establishes a scalable pathway from materials science to digital transformation, contributing to sustainable engineering, industrial innovation, and Europe's green and digital transitions.

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