EuroSun2026

GRAPH-BASED HYDRAULIC NETWORK MODELLING OF COMPLEX HEATING PLANTS FOR AUTOMATED FAULT DETECTION

Summary

Modern heating systems with high shares of renewable energy are increasingly complex, making operational faults of hydraulic origin difficult to detect. Thermohydraulic simulation models used as digital twins offer a promising approach for monitoring and fault detection, but manual model development remains prohibitively labour-intensive. This paper presents a methodology for the automated generation of hydraulic network models from graph-based system descriptions. The hydraulic topology is extracted from digital planning data and transformed into a calculation graph, from which a Simscape network model is generated automatically. The model computes quasi-stationary flow distributions based on direction-dependent pressure loss characteristics described by a polynomial parametrisation. Specific modelling challenges of heating plant hydraulics are addressed, in particular direction-dependent component behaviour and the interaction of multiple flow paths in meshed networks. The methodology is demonstrated on a complex hybrid heating system and is designed for integration into a coupled thermohydraulic digital twin framework.

Keywords: hydraulic network modelling, automated model generation, digital twin, fault detection, heating systems, graph-based simulation,

Field of application for the findings: Monitoring, fault detection and operational optimisation

Addressed audience: Researchers and engineers in HVAC system simulation, building energy system design, and operational monitoring of renewable heating systems

1. Introduction

The transition towards renewable heating leads to increasingly complex and individually designed heat supply systems for buildings. Especially in multi-family buildings, non-residential buildings, and small district heating networks, such systems typically integrate multiple heat generators, thermal storages, and diverse hydraulic circuits with complex control strategies. These systems occupy a middle ground between single-family houses with more standardised configurations and large-scale district heating plants with dedicated operations and monitoring personnel. Being individually designed but typically lacking continuous expert supervision, they are particularly susceptible to operational faults that remain undetected for long periods. Many of these faults are of hydraulic origin, such as incorrectly sized pumps, malfunctioning valves, excessive pressure losses, or unintended reverse flows. Hydraulic faults are particularly difficult to diagnose, as the interdependence of components in meshed systems means that symptoms often appear far from their actual cause.

Thermohydraulic simulation models coupled with operational data, commonly referred to as digital twins, provide a promising approach for systematic fault detection and performance monitoring. However, their practical deployment is often hampered by the high manual effort required to create and adapt such models, particularly for individually designed systems.

Automated model generation from digital planning data has been demonstrated for building simulation, including simplified HVAC representations (Jansen et al., 2021). For the internal hydraulics of heat generation systems, however, a higher level of detail is required to enable fault detection. Graph-based approaches to hydraulic network modelling and simulation are well established for district heating networks, both for automated system description (Fuchs, 2017) and for numerical solution of the hydraulic operating point from network topology and component characteristics (Stevanovic et al., 2007; Tol, 2021). In such applications, the hydraulic problem is often simplified by predominantly tree-like topologies where pipe friction governs pressure distribution, by prescribed flow rates at consumer substations, or both. The internal hydraulics of heating plants are characterised by different conditions: compact and strongly meshed topologies with multiple interacting pumps, direction-dependent component behaviour, control-induced operating mode switching, and tightly coupled parallel flow paths where no branch flows can be prescribed externally. This paper presents a graph-based methodology for the automated generation of hydraulic network models that addresses the specific requirements arising from component diversity and hydraulic complexity of commercial-scale heating plants.

2. Methodology

2.1 System graph representation and hydraulic network generation

The complete system topology is represented as a directed graph, where individual components (pipes, pumps, valves, heat exchangers, storages) form the nodes. Typed edges distinguish between hydraulic connections, signal connections, and energy flows. This graph serves as the common data structure from which different domain-specific models can be derived.

From the system graph, a hydraulic calculation graph is derived by extracting the hydraulic subsystem and applying a contraction algorithm: serial components between hydraulic junctions are aggregated into single edges, each representing one branch of the hydraulic network. The contracted graph preserves the network topology while reducing the system to its hydraulically relevant structure. From this graph, a system of nonlinear algebraic equations can be derived using methods of network analysis (mass conservation at junctions and pressure equilibrium along closed loops) and solved numerically. Alternatively, and to allow for better integration with existing simulation environments and component model libraries, the graph can be translated automatically into an acausal physical network model in Simscape (MathWorks), where the solver implicitly enforces the same conservation laws. Both approaches are implemented through a Python/NetworkX-based toolchain that generates either the equation system or the Simscape component code (SSC) and corresponding MATLAB scripts from the contracted graph.

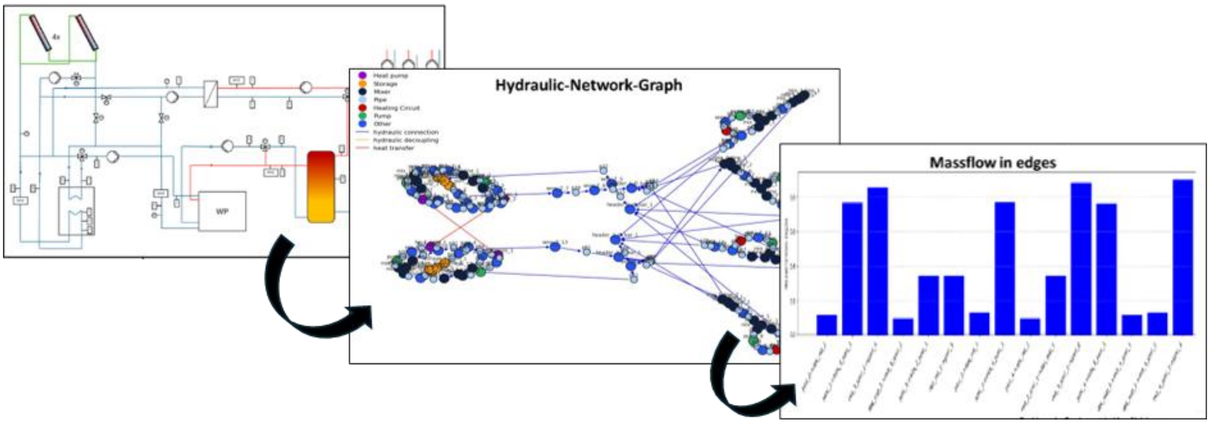

Figure 1: Methodology overview: From system diagram to digital plant representation as a network graph, to hydraulic simulation result (mass flow in hydraulic branches)

2.2 Modelling architecture: separation of hydraulic network and component models

To solve the hydraulic network, the pressure loss characteristic of each branch must be known, which in turn depends on the properties and operating state of the components contained in that branch. This leads to a separation into two model domains.

The hydraulic network model solves for the distribution of mass flow rates and pressure losses across the entire network, given the pressure loss characteristic of each branch. The component models describe the internal behaviour of each component — heat transfer, thermal losses, control response — and determine the corresponding pressure loss characteristic. Both domains are coupled but solved independently.The interface between both domains is the pressure loss characteristic: each component model provides its pressure loss coefficients to the corresponding network branch, and the network model returns the resulting branch mass flow rates. This forms a bidirectional coupling that is resolved at each simulation time step. The separation provides a defined interface for coupling component models from different sources, and allows the hydraulic network structure to be generated automatically from the system topology. Both model domains are integrated into a common Simulink system model. The toolchain generates MATLAB code that automatically assembles the complete model, including the hydraulic network and the component models with their signal interconnections, from the component information available in the system graph. The component models are based on the CARNOT Blockset for MATLAB/Simulink, while the approach also allows integration of manufacturer-specific component and controller models.

2.3 Pressure loss parametrisation

Each hydraulic element is characterised by a quadratic pressure loss polynomial of the form

$$\Delta p = C + L \cdot \dot{m} + Q \cdot \dot{m}^2, \qquad \text{(eq. 1)}$$

where C represents a constant pressure contribution (e.g. pump head), L a linear loss term, and Q a quadratic friction term. This polynomial provides a unified description for a wide range of hydraulic components, from simple pipe sections to pumps and valves, and allows aggregation of serial components into a equivalent characteristic per branch. Some components exhibit flow direction-dependent pressure loss behaviour. Check valves, filters, or pumps, for example, have a hydraulic characteristic for reverse flow that differs fundamentally from the forward direction. To capture this, separate coefficient sets are defined for positive and negative flow directions ($C^+L^+Q^+$ / $C^-L^-Q^-$), with a smooth numerical transition between both regimes near zero mass flow

3. Application and outlook

The methodology is developed and tested using different real-world heating system configurations provided by an industry partner. In this contribution, the methodology is demonstrated on a complex hybrid system comprising a heat pump, an ice storage, a solar thermal array for ice storage regeneration, and a gas boiler as backup heat source. The system supplies both heating and cooling through a multi-circuit distribution system with hydraulic separation. The resulting hydraulic topology includes multiple parallel flow paths with variable-speed pumps, mixing and diverting elements, and switching between operating modes, which leads to varying flow states across the network. The system graph is derived from digital planning data and automatically transformed into the hydraulic network model. The generated model reproduces the expected flow distribution for different operating modes, including flow reversal in branches that change function between operating states, and captures the interaction between parallel flow paths driven by multiple variable-speed pumps. Flow distributions are consistent with manufacturer design data for the individual operating modes.

Current work includes extending the range of supported component types, validating the coupled thermohydraulic model against operational monitoring data, and investigating characteristic fault scenarios such as incorrectly dimensioned pumps, defective valves, and unintended hydraulic short circuits. The objective is to use the generated models for systematic fault detection by comparing simulated and measured system behaviour, as well as for performance optimisation by identifying deviations from intended design operation.

4. References

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