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DISTRICTLAB-H: A NEW TOOL TO OPTIMIZE THE DESIGN AND OPERATION OF DISTRICT HEATING AND COOLING NETWORKS

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ABSTRACT

This article introduces a new scalable thermal-hydraulic modeling framework for dynamic simulation of small to large-scale District Heating (DH) and Cooling (DC) networks. The roots of this new development are to be found in the need for a more efficient solver including an accurate substation model. Following a comprehensive literature review, the solver is presented and validated using existing dynamic experimental data for a straight pipe. In a following step, a real large DH network, from the city of Metz (FR), is modeled and simulated, with results showing good consistency with field data. The numerical efficiency of the proposed approach is then assessed, leading to a quasi-linear scaling of the algorithm up to sizes comparable to the largest DH systems in Europe and to performances that compares very favorably to other models described in the literature. This work opens pathways towards the definition of advanced network architecture and the optimization of design and control strategies. To illustrate these new possibilities, the last section briefly presents real life use cases addressed with the tool such as the evaluation of an innovative 3-tubes architecture, the network resizing for lowering the temperature and the real time control optimization of the supply temperature.

Keywords: District Heating, Dynamic simulation, Thermal-hydraulic solver, innovative District Heating concept

1. INTRODUCTION AND STATE-OF-THE-ART

Due to their inherent ability to integrate waste heat and renewable energy, District Heating (DH) networks are cost efficient systems for any policy targeting a reduction of greenhouse gas emissions [1]. Defining transition scenarios for DH networks towards higher generation systems [2], designing and refining new networks as well as optimizing the operation of existing systems are crucial tasks to meet the ambitions associated to the deployment of these DH technologies. Thermal-hydraulic simulation and more specifically predictive simulation should play a key-role in those processes. By predictive, we mean the ability to simulate accurately situations and arrangements that go beyond those already characterized by existing operational data. Among various methodological options, physical models relying on an explicit representation of every component are particularly relevant. Brange *et al.* [3] showed how network simulation could help to identify and solve bottlenecks issues. Tol and Svendsen [4] proposed a simulation-based methodology for improving the dimensioning of piping networks and network layout. Wang [5] and Hirsch *et al.* [6] both relied on heuristic optimization approaches combined with network simulation capabilities for the appropriate selection of relevant design and operating parameters. In all these approaches, the obtained results are sensible to the accuracy of the underlying network model, as evidenced by Guelpa [7] for district heating networks and Yliruka *et al.* [8] in the more general context of energy systems models. Our contributions consist in presenting and evaluating a scalable and precise thermal-hydraulic model for dynamic simulation of fully described DH networks.

The models related to the present work are of 1-D nature and of the pseudo-dynamic type, an approach combining steady-state simulation of the hydraulic part and transient simulation of the temperature and passive flow tracers transport problems. Three main difficulties characterize the current research efforts for obtaining accurate models of this kind: a fine resolution of the transportation problem, a consistent and predictive description of substation operation, and a good scalability and CPU performances for full representation of large-scale DH networks.

On the temperature transport problems, we can group available methodologies in two main categories, depending on whether the computational grid remains at the node level, i.e. the pipe extremities, or meshes the pipe. The former category groups smart plug-flow models, sometimes labeled node methods, which compute transportation times between pipe extremities for modeling temperature profiles. Heat storage in the solid part of the pipe is accounted for by lumping a mass related to a pipe and modeling it at one extremity [9]. Some of the schemes proposed can be unconditionally stable ([10], [11]). However, the

lack of a computational grid inside the pipe decouples the internal temperature profile from other parts of the system. This is quite limiting when significant heat flow can occur between pipes, such as in the twin-pipe arrangement. Concerning methodologies equipped with in-pipe computational grids, the main issue mentioned in the literature concerns numerical stability; many proposed schemes can ensure a contained numerical diffusion, but are limited in regions where a suitably defined Courant number is lower than one ([12], [13], [14], [15]). On the opposite, an unconditionally stable, but quite diffusive stable implicit first-order upwind Finite Volume scheme (hereafter denoted UFV), has been described [16].

On the substations side (assumed here as indirectly-connected type substations), the primary outlet temperature at the substation level, hereafter denoted $T_{out,p}$, is of prime order on the thermal-hydraulic behavior of a DH network. Many tools available today ([17], [18], [19]) will rely on the setting of this $T_{out,p}$ variable in one way or another by the user; this, in particular in order to ease the numerical process of solving a thermal-hydraulic state. Another possibility consists in relying on a heat exchanger model to evaluate $T_{out,p}$. Benonysson *et al.* [20] and Giraud *et al.* [21] followed a grey-box modelling approach and proposed various forms of explicit empirical models linking inflow/outflow temperatures and flow variables. First principles models relying on the ε -NTU (i.e. effectiveness-number of transfer units) formulation or the mean logarithmic temperature difference formulation have been also proposed ([22], [7]). However, the integration of such models in a thermal-hydraulic simulation engine suitable for large-scale systems, comprising several hundreds or even thousands of substations, remains undone.

Finally, concerning scalability, several authors have developed DH simulation models at the district-scale using general-purpose environments. The equation-based Modelica language and the Dymola platform have been extensively used ([23], [21], [24]). A meshed DH network simulator in MATLAB/Simulink [25] and a plug-flow model for the TRNSYS software [26] have been developed. However, to simulate large-scale systems, a tool specifically crafted for this task is required. Guelpa *et al.* [27] proposed a dedicated thermo-fluid model to this end but the obtained computational costs were too high for the direct simulation of the DH system of the city of Turin, which is the largest in Italy. Omitting the imposed $T_{out,p}$ issue mentioned in the previous paragraph, existing commercial software could be used, but they additionally are limited by their capacity to handle dynamical scenarios [19] or architectures beyond the classical two-tube designs ([17], [18]).

The present paper reports on our work to design, implement, validate and demonstrate the usage of DistrictLab-H, a new software targeting predictive thermal-hydraulic simulation of small to large-scale DH systems. The main design options for DistrictLab-H are the preference for “first principle” models, i.e. mass, momentum and energy balances, over empirical models, the use of unconditionally stable calculation schemes and the formulation of a compact yet generic modeling language. The key strengths and novelties of the tool are its abilities i) to model innovative architectures that go beyond the classical 2-tubes configuration, ii) to solve efficiently large-scale and meshed systems and iii) to compute accurately the primary outlet temperature at the substation.

The following sections of the paper are structured as follows. In section 2, the thermal-hydraulic models and equations are presented together with the solving strategy. In section 3, the temperature transport solver is validated and the model scalability is studied. In section 4, real-life case studies are presented. Finally, section 5 summarizes the obtained results and concludes the paper.

2. OVERVIEW OF DISTRICTLAB-H™

The present section presents the core equations of the models. Although, these are described from a District Heating network point of view, similar equations are used when dealing with District Cooling networks.

2.1. Model structure and definitions

The DH network model is structured using an oriented graph in which a node acts as a thermal-hydraulic connector and an edge represents either a distribution pipe or a substation. This formalism allows expressing the governing equations in matrix form. In this context, the connectivity matrix between two ensembles, say U and V , respectively of cardinality N_U and N_V , is defined as the $N_U \times N_V$ matrix whose non-zero entries all equal 1 and correspond to (i, j) pairs where element # i of U is “linked” to element # j of V . The exact meaning of the “link” is case dependent.

In this approach, several edges are connectable to a unique node but each edge must be connected to exactly one “inlet” and one “outlet” node. A “fixed grade” node is a point of known head or pressure, i.e. a node connected to a Boundary Condition of the Pressure Imposed type (BCPI), where flow can enter or exit the network. To increase expressivity of the formalism, distribution pipes can host modeling gadgets (e.g. pumps, heat generators, valves etc.) and a variant exists to represent substations. These elements allow modeling classical two-tube networks and more innovative architectures, as the one presented in Figure 1.

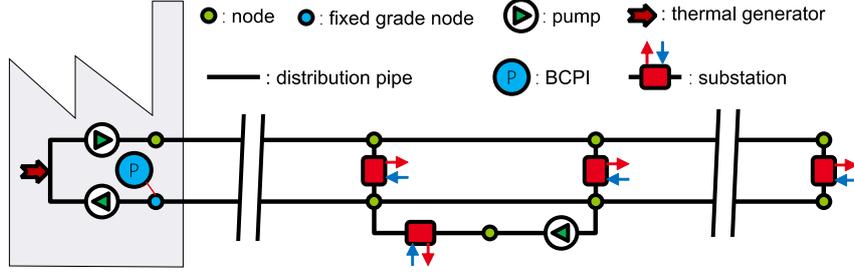


Figure 1. Schematic side-view of a model comprising a production unit, a 2-tube network and distributed consumers of various connection types.

The thermal-hydraulic kernel is built to treat 1D models of the pseudo-dynamic type, an approach combining steady-state simulation of the hydraulic part and transient simulation of the temperature transportation problem. This assumption is applicable for liquid water networks in which hydraulic wave travel several orders of magnitude faster than temperature and tracers waves and for problems where pressure transients can be discarded. Benonysson [9] and Boulos *et al.* [28] both demonstrated its efficiency respectively for DH dynamic simulation and contaminant propagation in water networks. A node is treated as an infinitesimal fluid volume hosting both a pressure and a temperature state whereas an edge is seen as a one-dimensional fluid element hosting a mass flow-rate state and an axially distributed set of temperature states.

2.2. Mass and energy balances at the node level

Let \mathbb{A}_+ (respectively \mathbb{A}_-) be the (node - edge) connectivity matrix where the “link” (as defined beforehand) means “is the inlet node of” (respectively “is the outlet node of”). Let \mathbb{B} be the (node - BCPI) connectivity matrix where the “link” stands for “is connected to”. With \overrightarrow{m}_e and $\overrightarrow{m}_{BCPI}$ respectively the edge and BCPI mass flow-rate vectors, mass conservation for all the nodes in the network reads in the matrix form as shown in Equation (1).

$$(\mathbb{A}_+ - \mathbb{A}_-) \cdot \overrightarrow{m}_e + \mathbb{B} \cdot \overrightarrow{m}_{BCPI} = \vec{0} \quad (1)$$

Pressure is imposed with Equation (2) in all fixed-grade nodes (BCPI ensemble), where \overrightarrow{P}_{st} and $\overrightarrow{P}_{st,BCPI}$ respectively stand for the node and BCPI stagnation pressure vectors.

$$\mathbb{B}^T \cdot \overrightarrow{P}_{st} - \overrightarrow{P}_{st,BCPI} = \vec{0} \quad (2)$$

To derive the energy balance equations at the node level, let $\overline{\mathbb{A}}_+$ (respectively $\overline{\mathbb{A}}_-$) be the (node - edge) flow dependent connectivity matrix where the “link” means “is the upstream node of” (respectively “is the downstream node of”). Similarly, let $\overline{\mathbb{B}}_+$ and $\overline{\mathbb{B}}_-$ be the equivalent matrixes for the (node - BCPI) ensembles. Energy conservation for all the nodes in the network reads as shown in Equation (3) with $T_{f,edge,out}$, $T_{f,BCPI,ext}$, $T_{f,node}$ and $\mathbb{D}(\)$ standing for the edge outlet temperature, the BCPI external temperature, the node temperature and the operator transforming a vector to the corresponding diagonal matrix respectively.

$$\mathbb{D}(\overrightarrow{T_{f,node}}) \cdot (\overline{\mathbb{A}}_+ \cdot \overrightarrow{m}_e + \overline{\mathbb{B}}_+ \cdot \overrightarrow{m}_{BCPI}) = \overline{\mathbb{A}}_- \cdot \overrightarrow{m}_e \cdot T_{f,edge,out} + \overline{\mathbb{B}}_- \cdot \overrightarrow{m}_{BCPI} \cdot T_{f,BCPI,ext} \quad (3)$$

2.3. Momentum and energy balance for a distribution pipe

In matrix form, the momentum balance equation written for the distribution pipes is shown in Equation (4), with g , ρ_f , z , D , A_f , and $\overline{\Delta H_s}$ standing for the gravity constant, the fluid density, the node altitude, the pipe diameter, the pipe cross-sectional area and the momentum source associated to pumping elements, respectively and ξ and f are non-dimensional factors respectively representing singular and regular friction losses.

$$(\mathbb{A}_{pipe,+} - \mathbb{A}_{pipe,-})^T \cdot (\overrightarrow{P}_{st} + g \cdot \overline{\rho_f \cdot z}) - \frac{1}{2} \cdot \mathbb{D} \left(\left(\xi + f \cdot \frac{L}{D} \right) \cdot \frac{|\overrightarrow{m}_{pipe}|}{\rho \cdot A_f^2} \right) \cdot \overrightarrow{m}_{pipe} + \overline{\Delta H_s} = \vec{0} \quad (4)$$

In the laminar regime, f is computed using the classical $64/Re$ law where Re corresponds to the Reynolds number. In the turbulent regime, f is evaluated using the law formulated by Swamee and Jain [29] as a function of Re , pipe diameter and roughness. Finally, the transition regime is approximated using a cubic polynomial designed such that the first derivative of

f remains continuous. Hydraulic singularities (e.g. bend, elbow ...) are accounted for considering constant singular pressure loss coefficients cumulated in the ξ factor.

To model temperature transportation, concentric “fluid” and “pipe wall” domains are included, surrounded by an insulation layer submitted to a user-defined external temperature. The model considers a convective heat transfer coefficient at the fluid-wall interface (denoted h_{fw}) and a user defined heat loss coefficient representing the insulation layer (denoted h_{ins}) but neglects the thermal resistances through the pipe wall. The h_{fw} coefficient is derived from correlations defining the Nusselt number ($Nu = h_{fw} \cdot D/\lambda$) as a function of the flow regime. A standard value of 4.36 is chosen for the laminar regime while in the turbulent regime, Nu is evaluated through an improved version of the original correlation [30], described in [31], and depends on Prandtl and Reynolds non-dimensional numbers.

The 1D energy balance equation along the x coordinate for the fluid domain follows the classical formulation, shown in Equation (5), with c_{p_f} , χ_{fw} and S_f respectively standing for the specific heat capacity, the heating perimeter and a conditional source term used to model the effect of a heat generator. The ‘w’ and ‘f’ indices respectively relate quantities relative to the wall and fluid domains.

$$\frac{\partial}{\partial t}(A_f \cdot \rho_f \cdot Cp_f \cdot T_f) + \frac{\partial}{\partial x}(A_f \cdot \rho_f \cdot Cp_f \cdot u \cdot T_f) = \chi_{fw} \cdot h_{fw} \cdot (T_w - T_f) + S_f \quad (5)$$

Similarly, the 1D energy balance equation along the x coordinate for the wall domain is shown in Equation (6).

$$\frac{\partial}{\partial t}(A_w \cdot \rho_w \cdot Cp_w \cdot T_w) = \chi_{fw} \cdot h_{fw} \cdot (T_f - T_w) \quad (6)$$

2.4. Momentum and energy balance for a substation

The model considered here represents a substation of the indirectly connected type composed of a service pipe and an ensemble consisting of a counter-current plate heat exchanger, a secondary temperature controller and an active two-way valve positioned on the primary side (see Figure 2).

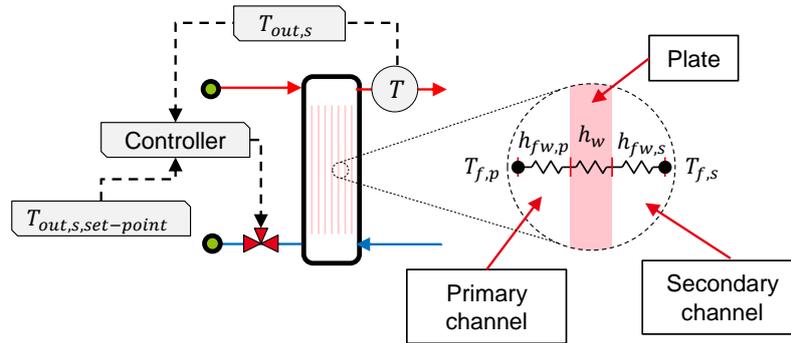


Figure 2. Schematic of the substation model.

From the hydraulic viewpoint, the model is similar to that of a distribution pipe so the corresponding equations set is similar to that already presented in Equation (4), with ‘pipe’ replaced by ‘sst’, $\overline{\Delta H_s}$ removed and the ξ factor representing the presences of the two-way valve and heat exchanger.

From the thermal viewpoint, 1D energy balance equations are written for both the primary and the secondary fluid streams within the heat exchanger. These streams are thermally coupled through a series of heat transfer coefficients accounting for conduction through the plate (h_w) and fluid-wall convection (hereafter denoted $h_{fw,p}$ and $h_{fw,s}$). Equation (7) shows this balance for the primary stream. The same equation is written for the secondary stream with index ‘p’ replaced by ‘s’.

$$\frac{\partial}{\partial t}(A_{f,p} \cdot \rho_{f,p} \cdot Cp_{f,p} \cdot T_{f,p}) + \frac{\partial}{\partial x}(A_{f,p} \cdot \rho_{f,p} \cdot Cp_{f,p} \cdot u_p \cdot T_{f,p}) = \chi_{fw} \cdot \frac{1}{1/h_{fw,p} + 1/h_w + 1/h_{fw,s}} \cdot (T_{f,s} - T_{f,p}) \quad (7)$$

The present model relies on a parametric law to estimate the fluid-wall heat transfer coefficients ($h_{fw,p}$ and $h_{fw,s}$) where the parameters are inferable from the values provided in typical heat exchanger data sheet. A two-coefficient power law with respect to the Reynolds number is therefore considered, as shown in Equation (8) with e , K and q respectively standing for the channel height, the constant and the power exponent of the law and the index ‘j’ is an alias for either ‘p’ or ‘s’. This equation can be viewed as a simplified version of the laws proposed by [32] and [33], discarding some dependencies to the plate geometry and Prandtl number. Typical values for q fall within the 0.6 – 0.8 range.

$$\frac{h_{fw,j} \cdot (2 \cdot e_j)}{\lambda} = \max(8; K_j \cdot Re^{q_j}) \quad (8)$$

2.5. Solving strategy

The global thermal-hydraulic model is computed relying on a hydraulic solver and a temperature transport solver, as shown in Figure 3. On the one hand, the hydraulic problem, which expresses mass and momentum conservation throughout the network, is a non-linear static problem and solves the pressure in the nodes and mass flow rates in the edges. On the other hand, the temperature transport problem, which expresses energy conservation throughout the network, is a quasi linear-problem and solves the temperature in the nodes, edges and substations.

Specifically, for each time-step, DistrictLab-HTM triggers several resolutions of the aforementioned two sub-problems in order to obtain a converged thermal-hydraulic solution. Optionally and after convergence of the thermal-hydraulic problem, DistrictLab-HTM can solve a scalar field linear dynamic transportation problem (transportation time, influence zone, etc.).

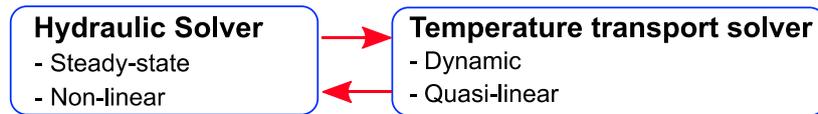


Figure 3. Main computation steps within the thermal-hydraulic solver

3. VALIDATION AND SCALABILITY

3.1. Transient temperature transport validation

The present section focuses on the error analysis for the temperature transport inside a single pipe submitted to varying inlet temperature. The main objectives here are i) to validate the temperature transport solver and ii) to evaluate an innovative discretization scheme based on donor-cell classical finite volume approach combined with a cell profile assumed as bilinear, coherent with what is expected in DH systems. The experimental data used for this validation were first presented by Sartor and Dewalef [34], and generously provided by one of the authors. Appendix A described the specific dataset used here.

Figure 4 (left) presents the results for Dataset 1 for which 2 steps are applied to the incoming water temperature. It highlights in the upper panel, the envelopes related to the imposed mass flow rate accuracy (+/- 3%) and in the lower panel, the uncertainty range for temperature measurement (0.9 K). The results are obtained for a converged mesh and a time step of 1s. A very satisfactory match between simulation and experimental results is proven with an instantaneous error remaining within the measurement system uncertainty range. It is worth emphasizing here that the transportation time is accurate even though the operating conditions simulated are extreme in terms of temperature ramp (about 90°C/min) with respect to normal operating conditions of heating grid production units (typically 5°C/min).

In order to compare the classical discretization scheme, denoted UFV, and the innovative one introduced above, denoted UFVbl, a mesh convergence analysis was conducted for different datasets and time steps. The resulting graphs are shown in Figure 4 (right) for both calculation schemes. Results show clearly that mesh convergence is attained for a Courant number (respectively cell size) one order of magnitude lower (respectively larger) for the UFVbl scheme. The latter results show the decisive advantage of the UFVbl scheme when dealing with large numbers of edges, since only a rather coarse grid is needed to obtain convergence. For both schemes, the error is shown to be the highest for the highest velocity dataset (Dataset 3), which is expected with finite volume schemes subjected to numerical diffusion. In Figure 4 (right), numerical diffusion clearly saturates the attainable accuracy, however, we believe that this accuracy is sufficient to conduct real-case studies on large-scale DH networks, as will be presented in the following section.

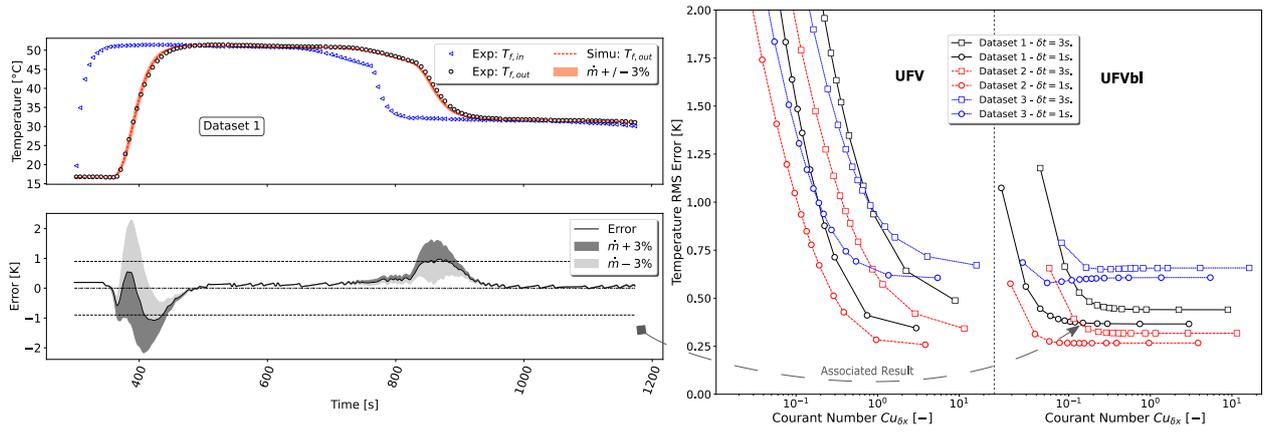


Figure 4. Left: Simulation results for Dataset 1 using the UFVbl scheme. Right: RMS error on the outlet pipe temperature for UFV and UFVbl calculation schemes as a function of the Courant number $Cu_{\delta x} = u \cdot \delta_t / \delta_x$, for 2 integration time steps (δ_t) and 3 datasets.

3.2. Large scale performances

The city of Metz, France, hosts a 2nd generation two-tube DH system with a yearly heat production of 450 GWh and 366 substations. Figure 5 (left) shows the layout of the Metz High Pressure Network (HPN) along with the position of the two supply units, namely SU1 and SU2, and five important substations, namely HPBP1 to HPBP5. Appendix B presents additional details of the HPN and describes the developed validation methodology.

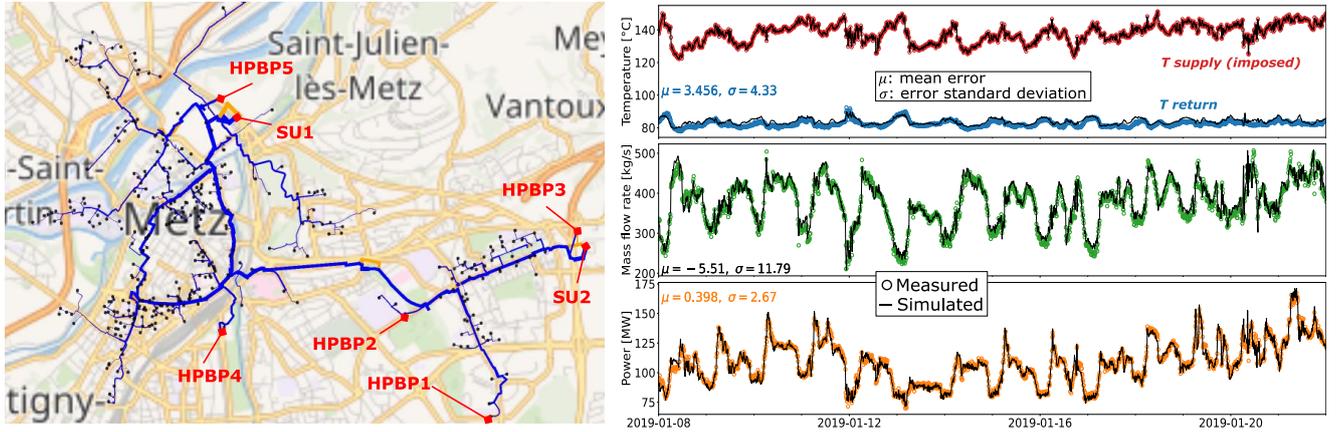


Figure 5. Left: HPN model for the DH system of Metz (base map from OpenStreetMap and OpenStreetMap Foundation, see www.openstreetmap.org). Right: Temperatures and mass flow rate at the main supply unit SU1 and total delivered power.

To verify the model, the numerical and experimental data were compared at the production level (see Figure 5 right) and at the consumer level (see Table 1) where the mean and standard deviation of a set of errors are denoted μ and σ respectively. These elements show that reasonable accuracy is obtained for such a large scale DH system. On-going work such as local pressure drop calibration helps to reduce the model uncertainties and will lead to a fully representative simulator.

Table 1. Error indicators obtained at the substation level for a two-week simulation of the Metz HP network.

	$\mu\{T_{in,pr}\}$ [K]	$\sigma\{T_{in,pr}\}$ [K]	$\mu\{T_{out,pr}\}$ [K]	$\sigma\{T_{out,pr}\}$ [K]	$\mu\{\Delta H\}$ [bar]	$\sigma\{\Delta H\}$ [bar]
HPBP 1	-2.44	1.31	-0.01	0.88	-0.06	0.42
HPBP 2	-2.24	1.88	+0.91	1.0	-0.46	0.48
HPBP 3	+1.47	3.06	+0.09	1.67	+0.19	0.43
HPBP 4	+1.00	1.35	-0.00	1.6	-0.44	0.18
HPBP 5	+1.74	0.82	+0.09	0.39	+0.02	0.05

3.3 Scalability

The scalability of the tool is now evaluated. Similarly to [27], the number of nodes N_n is used to quantify the problem size.

Figure 6 presents first the results obtained with the tool on a single core of an Intel i7@2.11GHz processor for a 10 minutes time-step. The number of nodes was artificially increased using replication of the Metz DH system (see section 3.2) with the replicas connected to nodes located close to the main production unit of this DH system. Interestingly, the proposed model scales quasi-linearly with N_n , at least up to $N_n = 6.5 \cdot 10^4$, which is the highest value tested. For illustration, this figure exceeds the size required to model the DH system of the city of Turin, which is among the largest in Europe.

The present results are also compared to available simulators and models published in the open literature.

Figure 6 plots the results obtained with the model described in Giraud et al. [35] and its larger-scale variants produced using the same method as previously, programmed using the Modelica language and simulated with the Dymola® simulation engine. In this case, the simulation time scales as $\propto N_n^2$.

Figure 6 also presents the CPU times reported in Guelpa et al. [27]. In this case, the execution time corresponds to a single iteration of a dynamic thermo-fluid model programmed and executed in Matlab®, using a 3.3 GHz CPU. Again, the CPU time scales as $\propto N_n^2$ and the results exhibit a cliff effect for N_n greater or equal to $2 \cdot 10^4$. It can therefore be concluded that for a given problem size, the execution of the present model is several orders of magnitude faster than with the other assessed tools.

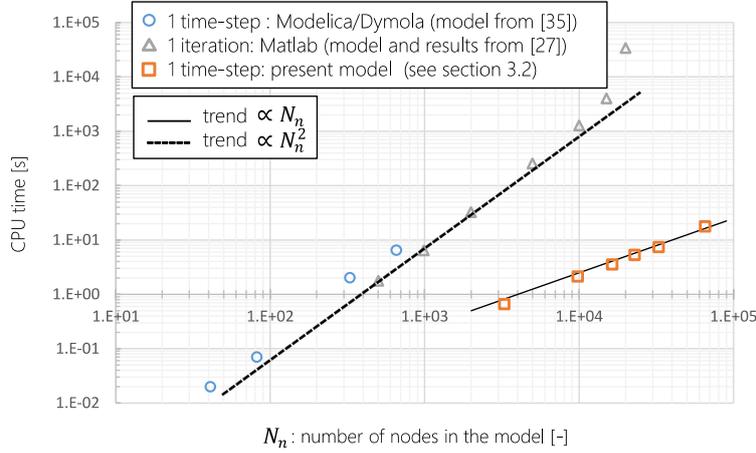


Figure 6. Influence of the problem size on CPU time for dynamic DH network simulation. The results concerning the Modelica and the present model have been obtained on the same computer using a 10 minutes time-step.

4. USE CASES

This last section illustrates the main use cases of DistrictLab-H™ with existing projects as example, pointing out the practical impact of the tool on the field. The following use cases share the common goal of improving energy efficiency of foreseen or existing DH systems by numerical means. These cases all rely on the development of a numerical model of the system. In practical terms, we relied on the tool’s automatic model builder allowing to set-up a network layout based on Geographical Information System (GIS) and to parametrize the consumers’ and substations’ models from energy consumptions. A few days of work is generally required to bring the model to a suitable readiness level. For each use case, the objectives and the approach are described, followed by the presentation of the main outcomes.

- **Use case 1: Assessing an innovative three-tube architecture to ease surplus heat integration.** District Heating networks have historically been designed to work in a context where energy sources were both abundant and flexible. These systems now face the challenge of abating carbon emissions of existing material. The “CADOuest” company [36], in cooperation with the “Services Industriels de Lausanne” [37], recently proposed an innovative concept based on an architecture allowing to connect new low temperature sources and consumers between the return line of an existing two-tube high temperature network (130 - 70) and a new third tube. Thanks to its versatility, DistrictLab-H™ was used to assess this architecture, to reveal and correct its potential weaknesses and establish its control rules. The project aims to deliver annually 11 GWh of low temperature heat, with a 90 % share of renewable energy [38].

- **Use case 2: Network resizing to lower operational temperature.** A large share of existing DH networks have been sized to operate at high temperature levels. However, in some cases, limited investments can be sufficient to ensure a transition towards lower network temperatures. The DistrictLab-H™ simulation engine is equipped with a resizing module allowing to automatically prescribe piping diameters required to satisfy local hydraulic design rules (velocity, pressure drop), in a multi-scenario context. This feature was recently applied to study the transition between an existing high temperature network to a lower temperature system for a French system. The results showed the techno and economic feasibility of the transition and helped to plan the project over a several years period.

- **Use case 3: Optimize the evolution of an existing network with respect to a temperature reduction target.** In the same context of a technical retrofit for existing, earlier generation DH networks, a methodology has been developed in order to tackle the design problem with a constraint in the network operating temperature target. Joint modifications of several elements at once (substations, pipes, hydraulic pumps) are assessed. This multi-asset perspective generalizes the approach of network resizing described above. With an objective set for the operating temperature, a multi-objective optimization problem is formulated for simultaneous minimization of investment costs and operation. This kind of study, implemented

through metaheuristics and using DistrictLab-H™ for evaluating operation costs of a solution candidate, takes advantage of the great performance of the simulator for its use in a typically costly optimization procedure (here an implementation of the NSGA2 algorithm [39]). After a thorough evaluation of the approach [40], a study in real, dynamical operating conditions for a DH network [41] showed its capacity to help decision makers on performing needed investment choices, by proposing sets of solution at different investment and operational costs.

• **Use case 4: Optimizing real-time supply temperature control.** Most two-tube DH Networks are operated relying on both variable supply temperature and differential pressure setpoints. These degrees of freedom are useful to secure the energy delivery to the consumers but can be very hard to set in practical situations. We developed and deployed two real-time supply temperature controllers on the DH systems equipping the French cities of Metz and Grenoble respectively [42]. These are based on the DistrictLab-H™ on-line module. As shown in Figure 7, in the Grenoble case, the systems works in tight connection with the Energy Optima 3™ production planner [43] (provided by Energy Opticon company) and targets a global production and distribution optimization. The installation of the system on the field to aid the decision of the operator revealed temperature reduction potentials of 15 degrees in some portions of the network.



Figure 7. Optimizing real-time supply temperature control combining DistrictLab-H™ and Energy-Optima™

5. CONCLUSION AND PERSPECTIVES

In this paper, we present a new tool, i.e. DistrictLab-H™, for the predictive simulation of district thermal networks. After reviewing the relevant scientific literature and available tools, the proposed thermal-hydraulic models and solver are detailed. In the present approach, the main models being of the first principle type, their validity is expected to go beyond situations and arrangements already characterized by existing operational data.

The innovative discretization scheme for the temperature transport solver is then validated and shown to behave favorably with respect to the classical first-order upwind finite volume scheme. The large scale performances of the solver are then evaluated with the modeling of the Metz (FR) DH network, which is the 3rd largest such system in France. The good accuracy of the model for the prediction of return temperatures, a crucial advantage, is shown. The quasi-linearity of the solver execution time with respect to the number of nodes in the model is demonstrated up to $6.5 \cdot 10^4$ nodes, which is the range for the largest DH systems in Europe. These performances compare very favorably to other models described in the literature.

To illustrate the new possibilities offered by the tool, the last section briefly introduced several real life use cases. An assessment for an innovative 3-tubes architecture for low temperature heat surplus integration has been performed. Additionally, network resizing for lowering the temperature could be tackled using a meta-heuristics approach with DistrictLab-H™ positioned as simulator. Finally, the predictive capabilities of the simulator allowed to perform real-time optimization of production supply temperature for two large DH networks; operational margins up to 15K were found in some portions of the networks.

On-going research efforts include further validation of systems including thermal energy storage and pairs of pre insulated pipes buried directly into the ground. Also, a methodology for automatic hydraulic calibration of pipes roughness based on field data is under development. Regarding the application, the meta-heuristics approach for network resizing will be extended with the integration of distributed storages as additional operation assets.

REMARK

All the models and the solver described in this article have been implemented in the commercial DistrictLab-H™ software tool dedicated to dynamic simulation of large scale thermal networks [44].

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APPENDIX A – Experimental data description

The test rig, built in the Thermodynamics laboratory of the University of Liège for the characterization of temperature transportation in water networks, consists in an insulated steel pipe of 39m long for an internal diameter of 52.48mm. The liquid is introduced at a constant mass flow rate and temperature steps are applied. All details on the apparatus are provided in [34].

We choose to present here results on three specific datasets of the original paper for which velocities (u), Reynolds (Re) and Peclet (Pe) numbers range from 0.58 to 1.06 m/s, $4.8 \cdot 10^4$ to $8.2 \cdot 10^4$ and $2.0 \cdot 10^5$ to $3.7 \cdot 10^5$, respectively. For these operational values, the flow is always turbulent and axial thermal diffusion is negligible. Moreover, the specific Richardson number, denoted Ri_s , accounting for the dynamic of the applied temperature step, remains very low, which according to Tenchine and Gauthé [45] rules out thermal stratification effects. Table 2 summarizes the information about these 3 datasets.

Table 2. Mean figures regarding the dataset considered.

	Reference name in [46]	u [m/s]	T_f [°C]	Re [-]	Pe [-]	Ri_s [-]	Pr [-]
Dataset 1	PipeDataULg150801	0.58	41.4	$4.8 \cdot 10^4$	$2.0 \cdot 10^5$	$6.3 \cdot 10^{-5}$	4.22
Dataset 2	PipeDataULg151204_1	0.75	29.5	$4.9 \cdot 10^4$	$2.7 \cdot 10^5$	$1.1 \cdot 10^{-5}$	5.48
Dataset 3	PipeDataULg160118_1	1.06	38.1	$8.2 \cdot 10^4$	$3.7 \cdot 10^5$	$8.6 \cdot 10^{-5}$	4.51

APPENDIX B – Metz DH Network presentation and validation methodology

The Metz DH consists of a High-Pressure Network (HPN) feeding customers and 7 secondary low-pressure networks. In the present work, we modeled the HPN, i.e. a pressurized water two-tube meshed network comprising two supply units and a booster pumping station. The HPN is operated with forward temperatures in the 105 to 160 °C range, relies on distribution pipes laid in concrete ducts and hosts substations of the indirectly connected type. The simulator was obtained by an automatic translation of a pre-existing model derived for a static simulation program comprising 3270 nodes, 3658 distribution pipes and 366 substations.

The formal validation of such large-scale simulator, affected by many sources of uncertainty including imprecisions on the network geometry and lack of experimental data at the consumer level, exceeds the scope of the present paper. However, for verification purposes, the model was simulated on a two weeks winter period using a time step of 10 min, which coincided with the measured data resolution. Based on the findings of section 3.1, the UFVbl computational scheme was used together with a maximum mesh size of 40 m, leading to $Cu_{\delta x}$ numbers greater or equal to one for velocities greater or equal to 0.06 m/s. When possible, time series provided by the operating company were used as boundary conditions for the simulation. This is the case for the set-point temperature of the supply units, for the head gain or mass flow-rate across the pumps and for the $\{T_{in,s}, T_{out,s, set-point}, \dot{Q}\}$ triplet of the monitored consumers (5 out of 366). For the other consumers, default laws

provided by the operating company to model $T_{in,s}$ and $T_{out,s,set-point}$ were used and the heating load \dot{Q} was deduced from the energy consumption provided by the billing system and a top down mechanism based on the total heating power of the production units.