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Mesh-Independent Water Pipe Cooling Method and Local Thermal Non-Equilibrium Effect in Mass Concrete Temperature Control Simulation

Linhui Gong¹, Jie Wu², Lei Shen^{2,*}, Jinlong Wang³, Hao Yin⁴, Giovanni Di Luzio⁵ and Maosen Cao⁶

¹School of Engineering, Nanjing Normal University Zhongbei College, Danyang, China

²College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing, China

³Water Resources Research Institute of Shandong Province, Jinan, China

⁴Department of Engineering, University of Cambridge, Cambridge, UK

⁵Department of Civil and Environmental Engineering, Politecnico di Milano, Milano, Italy

⁶College of Mechanics and Engineering Science, Hohai University, Nanjing, China

*Corresponding Author: Lei Shen. Email: shenl@hhu.edu.cn

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ABSTRACT: Pipe cooling is a primary method for temperature control in mass concrete construction. The optimization of cooling pipe layout in practical engineering calls for the development of new simulation methods that combine computational accuracy with efficiency. This study presents a mesh-independent method for thermal analysis of pipe cooling in mass concrete structures. Two energy balance equations are established for the water pipe, modeled using lattice elements, and for the concrete, modeled with hexahedral solid elements. The local thermal non-equilibrium (LTNE) effect is captured through heat exchange between the two domains, facilitated by spatial topological mapping. Compared with experimental data and conventional simulations, the proposed method eliminates the need for remeshing the concrete domain when the pipe layout is altered, while maintaining a high level of computational accuracy and efficiency. The temperature difference caused by LTNE effect and daily pipe flow reversal significantly increases early-age cracking risk.

KEYWORDS: Mass concrete; water pipe cooling; mesh independence; spatial topological mapping; local thermal non-equilibrium

1 Introduction

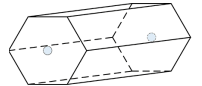
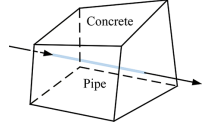
During the concrete pouring process, the continuous exothermic reaction of cement hydration results in non-uniform temperature distribution within the structural interior. Under the combined effects of adverse ambient temperature and boundary constraints, temperature gradients and thermal stresses occur and then can easily lead to thermal cracking. Such cracking significantly compromises the safety and stability of concrete structures [1,2]. Apart from the pre-cooling concrete system [3], water pipe cooling technology exhibits remarkable potential for regulating the internal temperature distribution of concrete [4]. Developing precise numerical models for temperature fields in pipe-cooled mass concrete structures is of great engineering significance for predicting and optimizing their thermomechanical behavior [5–8]. Nevertheless, there are both challenges in the cooling pipe layout optimization for precise models and an oversight of local thermal non-equilibrium (LTNE) between cooling pipes and concrete in conventional methods.

To this end, all methods (summarized in Table 1) of water pipe cooling in literature can be divided into two categories. The first kind is the methods without the degree of freedom (DoF) of water pipe temperature,

which assume the heat exchange between water pipe and concrete as a local thermal equilibrium problem [1,9]. This kind of method has high efficiency and does contribute to mass concrete construction at the age without high performance computers. Refs. [10,11] improved the equivalent water pipe cooling method by functional theory to consider the pipe orientation and length within the concrete element; see Fig. 1a. This approach embeds cooling pipes internally within conventional concrete elements and incorporates the heat dissipation surfaces at the concrete-pipe interface as boundary conditions in the governing equations. By superimposing the energy dissipated through the cooling pipe walls onto standard functional formulations, finite element governing equations for concrete structures containing cooling pipes are systematically derived based on variational principles. The method enables cooling pipes to traverse arbitrary positions within concrete elements, thereby circumventing increased complexity in mesh partitioning. However, the water mass flow along the pipe is so fast that heat exchange between pipe and concrete cannot be simplified to a local thermal equilibrium [12]. This condition in fact means it is not accurate enough.

To gain a highly accurate prediction of temperature distribution in mass concrete, researchers further develop models with DoF of water pipe temperature. This category splits the concrete element into pipe elements and concrete elements based on different novel structured approaches. Recently, computational fluid mechanics [13] associated with machine learning [14] is also adopted in cooling pipe simulation. Refs. [15–17] developed a series of numerical methods for analyzing temperature variations along water pipelines through direct surface integration along element boundary surfaces. To address the serpentine arrangement of cooling water pipes in practical engineering applications, these methodologies employ an adaptive grid search algorithm that utilizes the geometric parameters (coordinates and radius) of pipe elements to perform curved surface integration along the pipeline path. This approach demonstrates enhanced capability in simulating the actual flow trajectory within water pipes and accurately calculating the axial and radial temperature gradients. Nevertheless, all these kinds of methods have limitations in concrete discretizations constrained by pipe layout, and, more seriously, require regeneration of concrete mesh when the pipe layout is modified.

Table 1: Comparison of grid relationships and characteristics for various methods.

Method	Grid Relationship	Characteristics	Schematic Diagram
Equivalent heat conduction method [1]	Ordinary element without pipe	1. Constant cooling water temperature along pipe (low accuracy); 2. Low mesh count (high efficiency)	 Pipe-equivalent concrete element
Functional method [10]	Ordinary element without pipe	1. Cooling water temperature variation along pipe (moderate accuracy); 2. Low mesh count (high efficiency); 3. Insufficient accuracy of pipe water temperature	

(Continued)

Table 1 (continued)

Method	Grid Relationship	Characteristics	Schematic Diagram
Heat-fluid coupling method [18,19]	Truss (line) pipe elements along edges of concrete elements	1. Cooling water temperature variation along the pipe (high accuracy); 2. Low mesh count; 3. Mesh generation dependent on pipe layout	
Composite element method [15]	No solid pipe elements are generated in concrete elements; instead, the heat exchange is computed based on concrete zones	1. Cooling water temperature variation along pipe (moderate accuracy); 2. High mesh count/Large number of elements; 3. Insufficient accuracy of pipe water temperature	
Superposed element method [17]	Solid pipe elements are generated within concrete elements, but both meshes are independent of each other in space	1. Pipe temperature variation along the pipe (high accuracy); 2. Large number of elements; 3. Interdependent mesh generation of pipe and concrete elements along the pipe length	

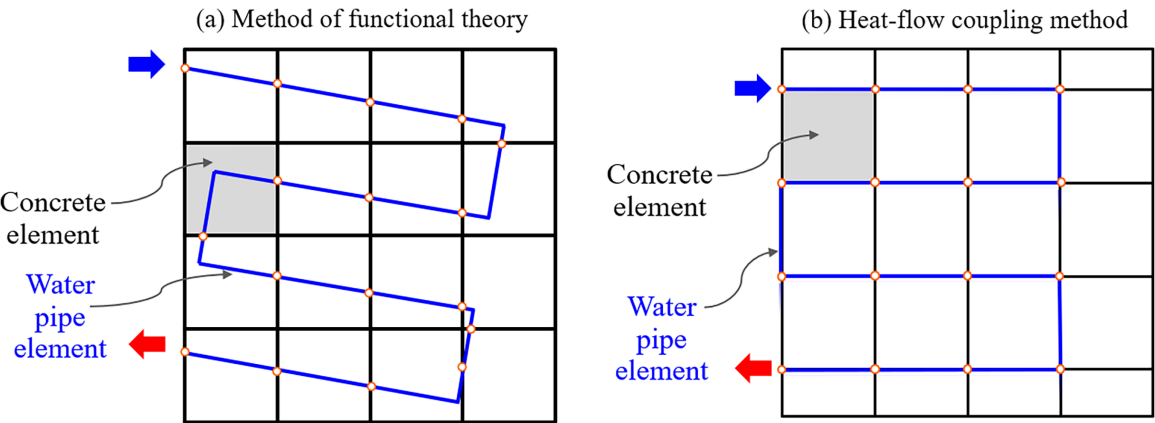


Figure 1: Illustration of pipe cooling method in literature. (a) Functional theory; (b) Heat-flow coupling method.

To overcome the difficulty of mesh refinement and increasing element numbers, Refs. [18,19] developed a thermal-flow coupling method that introduces independent degrees of freedom for pipes, where water pipe elements share nodes with solid concrete elements; see Fig. 1b. This method enables spatial heat exchange analysis between concrete and cooling pipes while avoiding increasing concrete mesh numbers. But, the discretization of mass concrete structures with complex geometrical configurations, which is difficult, is strongly constrained by water pipe layout. In fact, the adaptability to varying types of concrete elements,

and convenience for pipe arrangement modifications are more important to the optimization of pipe cooling scheme.

Previous approaches have endeavored to achieve a balance between computational accuracy and efficiency. However, their concrete meshing strongly depends on the complex spatial layout of the water pipe network. Hence, the layout optimization of cooling pipe for practical mass concrete structure requires to incorporate pipe element configuration with energy conservation principles for determining temporal-spatial temperature variations in pipes, as exemplified by the heat-flow coupling method [18,19]. Meanwhile, the simulation of LTNE between pipe and concrete also needs to be improved for functional methods [10]. This work proposes a novel water pipe cooling method that precisely computes temperature variations along pipe paths based on the thinking of dual-lattice topology [20,21] for multi-physics coupled problems. The rest part of paper is organized as three parts. Section 2 presents the theory of mesh-independent water pipe cooling method. Section 3 validates the proposed method based on a single-pipe cooling experiment. Section 4 reports the model capability of mass concrete at early age cooled by multi-pipes.

2 Mesh-Independent Water Pipe Cooling Method

In this section, a novel method-independent method for simulating temperature changes in mass concrete, termed the mesh-independent method for water pipe cooling (MIM), is presented.

2.1 Method Principle

The fundamental principle of the mesh-independent water pipe cooling method is illustrated in Fig. 2. The whole system comprises concrete elements and water pipe elements. The water pipe elements are generated based on the spatial overlap between the water pipe layout and concrete elements. Each pipe element connects two concrete elements across their shared surface as shown in Fig. 2a. This definition transforms the heat flux from the local coordination of real water pipe segments to the local coordination of concrete element, which is consistent with the process of matrix assembly prior to solving the balance equations. In other words, this equivalence has no influence on the modeling accuracy provided that the correction for pipe segment length within the concrete element is accounted for in the governing equation. A key advantage of this approach is that the heat flux inlet and outlet due to pipe cooling in the concrete element does not change when the pipe layout undergoes slight dislocations as illustrated in Fig. 2c,d. Only when the pipe layout is completely redesigned must the water pipe elements be regenerated within the unchanged concrete mesh; see the condition in Fig. 2d. The decoupling of the concrete mesh from the pipe layout represents the primary innovation of this work. The pre-process steps are as follows:

1. Discretize the mass concrete domain with an arbitrary grid.
2. Identify all physical water pipe layouts aligned with concrete mesh.
3. Identify all concrete elements through which a pipe passes. One simple approach is to point out the concrete element with pipe inlet, so that the other elements can be determined from their adjacent elements based on water pipe layout.
4. The geometric center of each such element is computed and defined as a node for the equivalent pipe element.
5. Create equivalent lattice elements for water pipe by sequentially connecting these nodes. The length of each pipe element (l_p) is calculated and stored.
6. Calculate the embed length of actual pipe segment (l_{ps}) contained within it within each concrete element, including segments crossing concrete element surfaces.

7. Export the mapping relationships between pipe elements and host concrete elements to an external file. This file is read into memory at the start of the simulation to perform the heat exchange with the feature of LTNE.

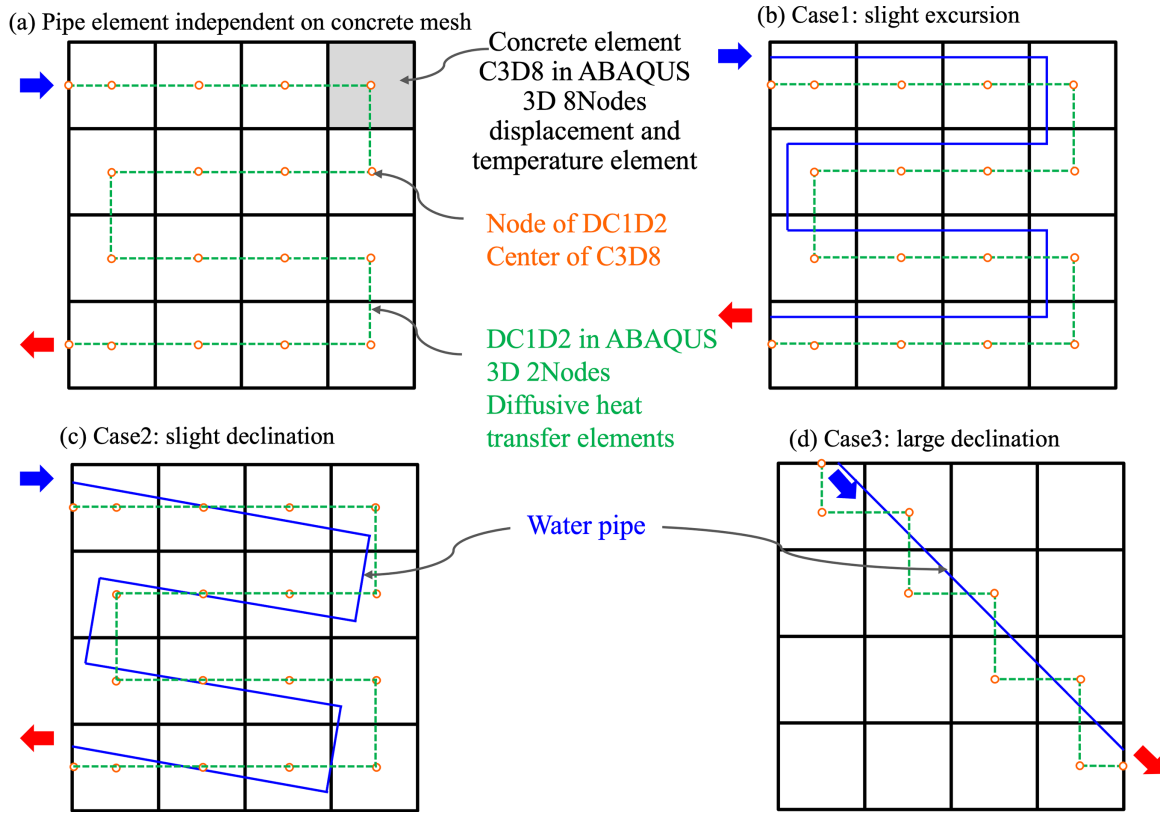


Figure 2: Illustration of mesh-independent water pipe cooling method. (a) Pipe elements definition; (b) Pipe elements with slight excursion of pipe layout; (c) Pipe elements with slight declination of pipe layout; (d) Pipe elements with large declination of pipe layout.

The proposed mesh-independent cooling method is implemented by solving two coupled energy balance equations within the ABAQUS UMATHT user subroutine. The computational workflow is illustrated in Fig. 3. The heat conservation problems in concrete elements incorporate cement hydration exothermic processes and heat losses due to concrete-pipe heat exchange. Conversely, the governing equation for the water pipe elements calculates the convective heat gain based on the retrieved concrete temperature field. At each time increment, thermal equilibrium between the two domains is enforced via preprocessed spatial mapping operators, guaranteeing global energy conservation. Updated temperature fields for both domains are then stored in external memory modules, ensuring data persistence for the subsequent iteration. The temperature fields stored in external memory modules will be read in solution-dependent state variables in the next time increment.

Theoretically, the proposed framework bears conceptual resemblance to functional theory formulations [10]. However, a fundamental distinction exists that the water temperature variation along the pipe is implicitly modeled via composite integration based on variational principles in functional methods, whereas the present formulation explicitly resolves the heat flux exchange at the pipe-concrete interface, without altering the enthalpy field within concrete elements. This explicit treatment significantly simplifies the computation and visualization of the DoF of water pipe temperature across the entire concrete domain.

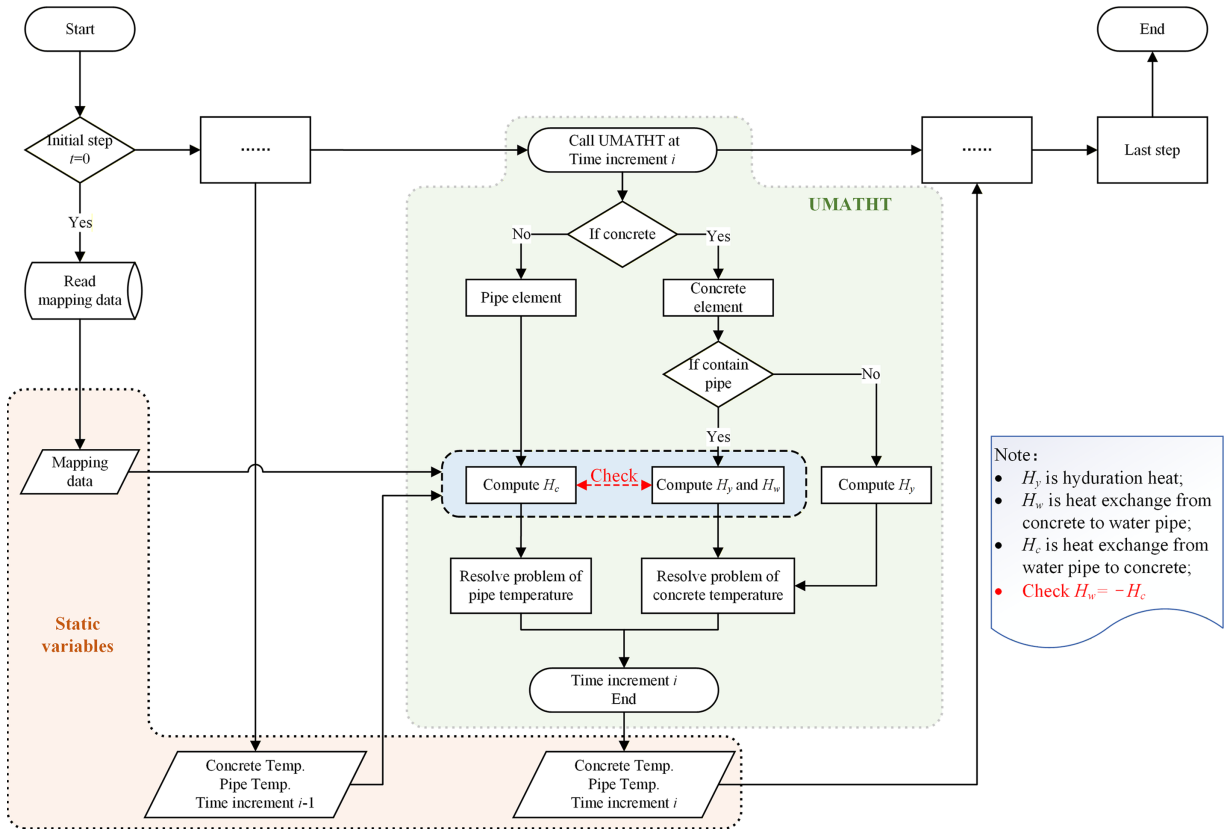


Figure 3: Workflow of mesh-independent water pipe cooling method.

Computationally, the proposed method shares similarities with thermal-flow coupling method [18]. It requires geometric conformity between the pipe elements and the edges of the concrete mesh. This imposes a significant constraint that any alteration to the cooling layout necessitates remeshing of the concrete domain. The present methodology overcomes this limitation by completely decoupling the discretization of the concrete from the topology of the pipe network.

2.2 Concrete Temperature

The temperature variation of mass concrete is mainly caused by the heat generation from hydration reaction (H_y) and heat exchange from concrete and also water mass flux in pipe (H_w). The general temperature governing equation of concrete is written as:

$$\rho_c c_c \frac{\partial T_c}{\partial t} = \lambda_c \nabla^2 T_c + \frac{\partial H_y}{\partial t} + \frac{\partial H_w}{\partial t} \quad (1)$$

where T denotes temperature (subscripts “c” for concrete and “p” for pipe), ρ_c is concrete density, λ_c is thermal conductivity of concrete, c_c is specific heat capacity of concrete, t is time. The thermal properties evolve with hydration degree [22]. The thermal conductivity decreases about 10% and heat capacity fluctuates within the range of 1300~1600 J/(kg · K). Here, these thermal properties are simplified as constants. H_y is the adiabatic temperature rise from cement hydration:

$$H_{y,I} = Q_0 [1 - e^{-m(t-t_0)}] \quad (2)$$

where Q_0 is the total hydration heat, m is the fitting coefficient based on experimental results, and t_0 is the casting time of concrete.

As illustrated in Fig. 4, each concrete element contains a pipe node N . The heat exchange (H_w) between concrete elements and two connecting pipe elements is computed as:

$$H_{w,I} = A_p \beta_p (T_{p,I} - T_{c,I}) \quad (3)$$

with $A_p = \pi d_p l_{pc}$ representing the contact area between water pipe and concrete, d_p as the external diameter of water pipe, and β_p the heat convection coefficient between water and concrete.

$$\frac{1}{\beta_p} = \frac{1}{\beta_w} + \frac{c_p}{\lambda_p} \quad (4)$$

where c_p is the thickness, λ_p is the thermal conductivity of pipe, and β_w is the convective heat transfer coefficient.

$$\beta_w = \frac{a Re^b Pr^c \lambda_w}{d_p} \quad (5)$$

in which, a , b and c are fitting parameters, $Re = (d_p - 2c_p) v_w \rho_w / \mu_w$ is the Reynolds number with the water velocity along pipe of v_w , water density of $\rho_w = 1000 \text{ kg/m}^3$ and dynamic viscosity of $\mu_w = 0.001 \text{ Pa} \cdot \text{s}$. $Pr = c_w \mu_w / \lambda_w$ is the Prandtl number with specific water heat capacity of c_w and water thermal conductivity of λ_w . It is suggested that $a = 0.023$, $b = 0.8$ and $c = 0.3$ in case of cooling.

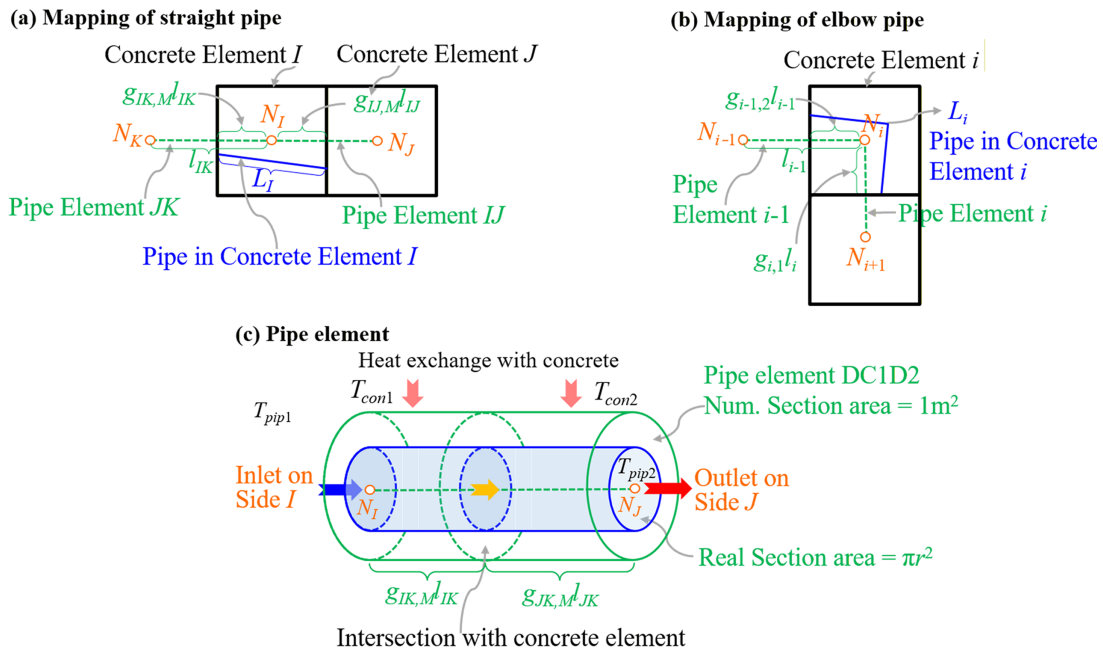


Figure 4: Illustration of element mapping. (a) Mapping of straight pipe; (b) Mapping of elbow pipe; (c) Pipe element.

2.3 Water Pipe Temperature

The temperature variation of water pipe is mainly caused by the heat exchange from concrete and also water mass flux in pipe. The thermal conduction of pipe is significant when the water flux is turn off. The governing equation of water pipe temperature is written as:

$$\rho_w c_w \frac{\partial T_p}{\partial t} = \nabla \left(\underbrace{\lambda_w \nabla T_p}_{\text{Fourier flux}} + \underbrace{c_w w_w T_p}_{\text{Dufour flux}} \right) + \underbrace{\frac{\partial H_c}{\partial t}}_{\text{Heat from concrete}} \quad (6)$$

where $w_w = s_p v_w$ is the water mass flux, s_p is the cylindrical pipe section-area and v_w is the water velocity in pipe.

As illustrated in Fig. 4, two adjacent concrete elements I and J have two center nodes N_I and N_J . The pipe element $N_I N_J$ represents the heat transfer from concrete elements I to concrete elements J due to the water mass transport across the sheared concrete element surface. Hence, the governing equation of water pipe element $N_I N_J$ within concrete elements I reads:

$$\rho_w c_w \frac{\partial T_{p,I}}{\partial t} = \lambda_w \frac{\partial^2 T_{p,I}}{\partial x^2} - c_w v_w \rho_w \frac{\partial T_{p,I}}{\partial x} + \frac{\partial H_{c,I}}{\partial t} \quad (7)$$

and the governing equation of water pipe element $N_I N_J$ within concrete elements J reads:

$$\rho_w c_w \frac{\partial T_{p,J}}{\partial t} = \lambda_w \frac{\partial^2 T_{p,J}}{\partial x^2} + c_w v_w \rho_w \frac{\partial T_{p,J}}{\partial x} + \frac{\partial H_{c,J}}{\partial t} \quad (8)$$

Dufour heat flux term has opposite sign since the water discharge from concrete elements I and charges into concrete elements J .

As one water pipe element has two segments within two concrete elements, the weighting coefficients $g_{p,I}$ and $g_{p,J}$ are defined to represent the pipe length difference within two concrete elements I and J . $g_{p,I} = l_{IJ,I}/l_{IJ}$ and $g_{p,J} = l_{IJ,J}/l_{IJ}$ are geometric proportions of distances ($l_{IJ,I}$ and $l_{IJ,J}$) from pipe nodes to the shared concrete element surface over the pipe element length (l_{IJ}), and these geometric coefficients satisfy the summation $g_{p,I} + g_{p,J} = 1$. The two weighting coefficients can describe straight and elbow water pipe elements that cross concrete elements of various sizes. Combining Eqs. (7) and (8), the energy conservation equation for one pipe element reads:

$$\rho_w c_w \frac{\partial T_{p,IJ}}{\partial t} = \lambda_w \frac{\partial^2 T_{p,IJ}}{\partial x^2} - c_w v_w \rho_w \frac{\partial}{\partial x} (g_{p,I} T_{p,M} - g_{p,J} T_{p,N}) + \frac{\partial H_{c,IJ}}{\partial t} \quad (9)$$

in which, the average temperature of pipe element can be computed as a linear interpolation $T_{p,IJ} = g_{p,J} T_{p,I} + g_{p,I} T_{p,J}$.

Similarly, the heat exchange flux from concrete element can be calculated as: $H_{c,IJ} = g_{p,J} H_{c,I} + g_{p,I} H_{c,J}$. The heat exchange from concrete element to pipe element is computed by:

$$H_{c,I} = A_p g_{p,I} \beta_p (T_{p,I} - T_{p,M}) \quad (10)$$

$$H_{c,J} = A_p g_{p,J} \beta_p (T_{p,J} - T_{p,N}) \quad (11)$$

when considering water pipe and mass concrete as one system, the heat gain of water should be equal to the heat loss of concrete. In the implementation, the geometry scaling between real pipe and 1D element (DC1D2 in ABAQUS) is used to meet the energy convergence.

$$H_{c,IJ} = -\frac{s_{unit}}{s_p} \frac{l_p}{L} H_w \quad (12)$$

in which, the section area for 1D element $s_{unit} = 1 \text{ m}^2$ (Fig. 4c), $s_p = \pi d_p^2/4$ is the section area of real pipe, l_p is the pipe element length and L is the real pipe length embed in concrete element (Fig. 4a,b).

3 Model Validation

This section validates the proposed model and examines the sensitivity to variations in mesh shape and size.

3.1 Experiment and Simulation Setup

The proposed method is validated against both numerical and experimental data from [23]. The validation involved two concrete specimens, including a reference block without pipes and a test block with a single straight cooling pipe. Each specimen measured 500 mm × 500 mm × 1000 mm. To minimize external thermal interference, all external surfaces were insulated with sandwich panels comprising two 12 mm-thick bamboo plywood layers and a 50 mm-thick XPS insulation plate inside with thermal conductivity of 0.03 W/(m · °C). In the test specimen, a cooling pipe with a constant water temperature of 18°C was placed centrally along the longitudinal axis (1000 mm dimension).

Temperature was monitored at the mid-span cross-section (500 mm along the longitudinal direction). As shown in Fig. 5a, three thermocouples were embedded 290 mm above the bottom of the specimen. They were positioned along a radial line at distances of 60 mm (Point C), 125 mm (Point B), and 200 mm (Point A) from the cross-section center.

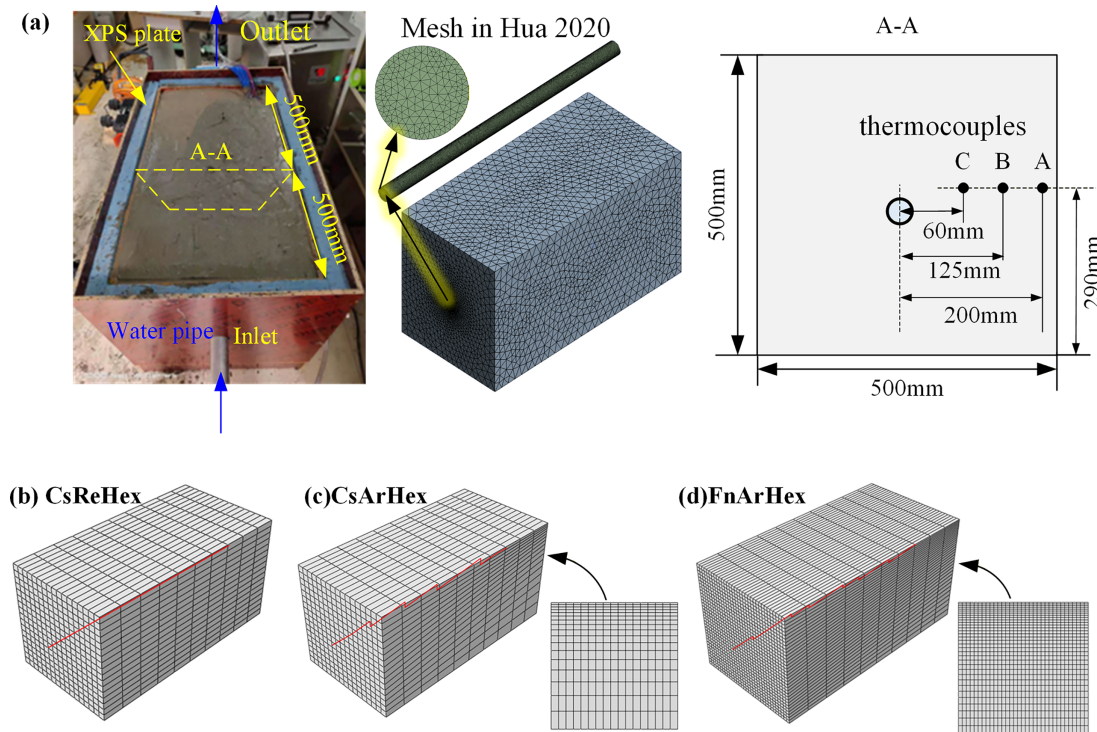


Figure 5: Illustration of experimental and numerical setup on case with one pipe. (a) Setup in [23]; (b–d) Discretizations with various mesh sizes.

The numerical models replicating the experimental conditions are shown in Fig. 5b–d. Three concrete meshes are considered, namely coarse regular hexahedral (abbreviated as CsReHex), coarse arbitrary hexahedral (abbreviated as CsArHex), and fine arbitrary hexahedral (abbreviated as FnArHex). The water pipe was discretized with lattice elements according to the geometric relationship between the concrete and the water pipe depicted in the pre-process steps in Section 2.1. When the concrete mesh consists of regular

hexahedra, the real water pipe is mapped as a straight line (Fig. 5b). For arbitrary hexahedral elements, the real water pipe mapping adapts to a segmented path, as illustrated in Fig. 5c,d.

Regarding computational efficiency, MIM requires only 1210~4410 hexahedral solid elements of concrete and 12~21 lattice elements of water pipe. In comparison, the conventional FEM model used by [23] contains 1,969,591 tetrahedral solid elements for both concrete and water, with shared nodes at the pipe wall enabling direct convection of hydration heat into the fluid domain. All material parameters in the simulation corresponding to the experimental values are given in Table 2.

Table 2: Parameters in simulation.

Material	Parameter	Section 3.1	Section 3.2	Unit
Concrete	Concrete heat capacity	970	820	J/(kg·°C)
	Concrete density	2500	2650	kg/m ³
	Concrete thermal conductivity	1.28	2.01	W/(m·°C)
	Adiabatic hydration temp. rise	56	29	°C
	m in Eq. (2)	0.79	0.79	–
Pipe	Water pipe external diameter	50	30	mm
	Water pipe thickness	2	1	mm
	Pipe Length	1.5	125	m
	Pipe thermal conductivity	202.4 (Al)	0.461 (Plastic)	W/(m·°C)
Water	Inlet water temperature	20	8	°C
	Inlet water velocity	0.1	0.45	m/s
	Water density	998.2	1000	kg/m ³
	Water heat capacity	4182	4182	J/(kg·°C)
	Water thermal conductivity	0.6	0.6	W/(m·°C)
Boundary	Ambient temperature	20	16	°C
	Heat exchange coefficient to air	0.532	–	W/(m·°C)

3.2 Mesh Independence

The material parameters and boundary conditions listed in Table 2 are first calibrated against the measured adiabatic temperature rise at the specimen center. As shown in Fig. 6a, the calibration yields a total temperature rise of 46°C and $m = 0.79$ in Eq. (2), an ambient temperature of 20°C and a surface heat exchange coefficient of 0.532 W/(m·°C) are determined. The simulated temperature curve nearly overlaps the experimental data in the post-peak phase, while a noticeable delay occurs during the temperature ascent due to the exponential function of Eq. (2).

Subsequently, the simulation incorporating the cooling pipe is validated against experimental data at Points A, B, and C, as presented in Fig. 6b–d. Excellent agreement across all mesh configurations (CsReHex, CsArHex, FnArHex) confirms the model's accuracy. A comparison between the CsReHex and CsArHex results shows the maximum temperature deviation at Point A, with an absolute error of 0.4°C (relative error 0.7%). Conversely, comparing CsArHex with FnArHex reveals the largest discrepancy at Point C, with an absolute error of 1.34°C (relative error 3.2%). These minor deviations demonstrate that the model's predictions are effectively independent of both concrete mesh size and element shape.

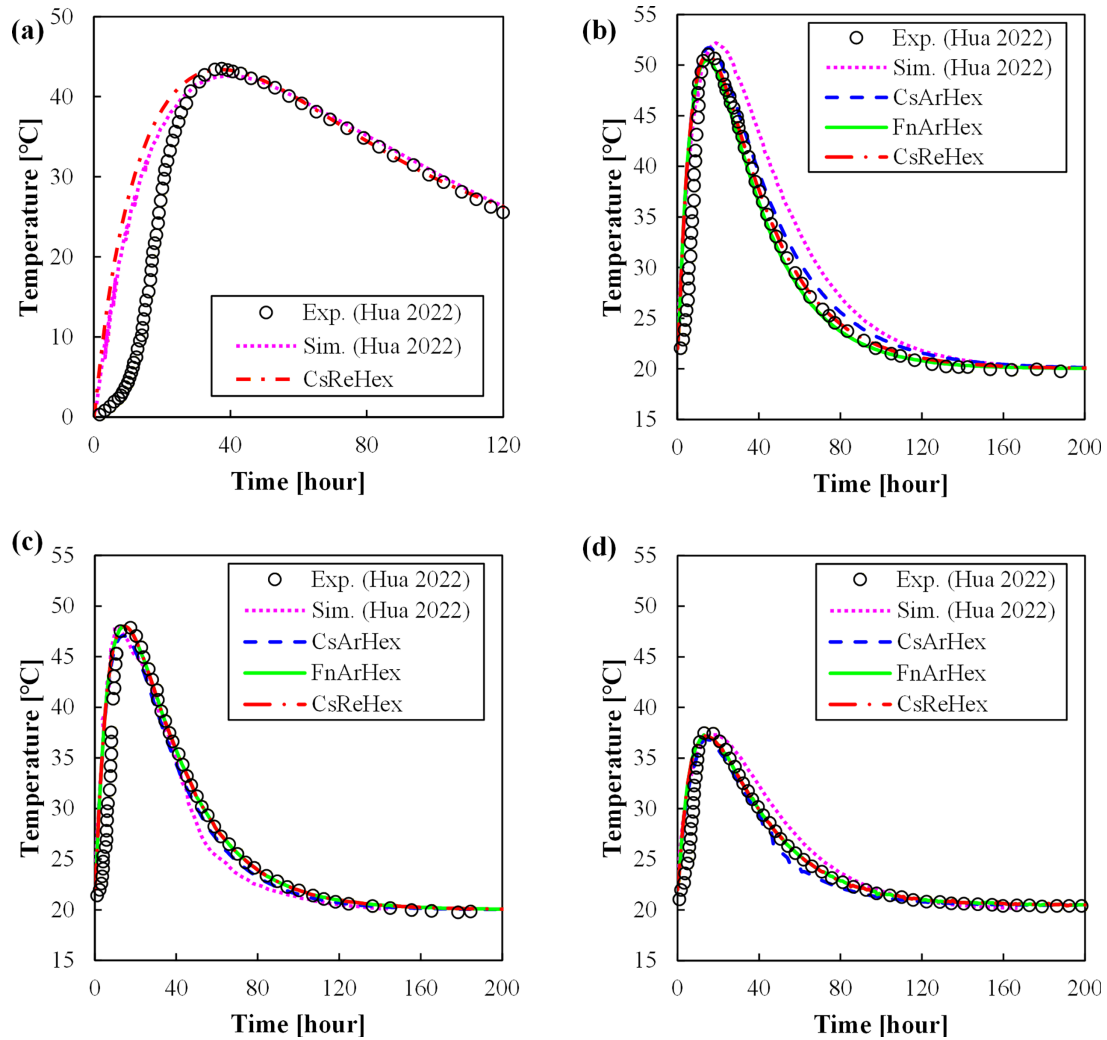


Figure 6: Results for the single pipe case. (a) Adiabatic temperature rise; (b) Point A; (c) Point B; (d) Point C.

Furthermore, the predictive capability of the proposed method, despite its significantly coarser discretization, matches that of the conventional high-fidelity FEM model in [23], which employs 1,969,591 tetrahedral elements. Remarkably, a full 200-h test duration with the proposed model completes within 15 min on a standard laptop equipped with an 8-thread i7-10875H CPU.

4 Model Capability

The model capability for mass concrete structures is evaluated using the experiment results from [18,19] in this section.

4.1 Simulation Setup

A full-scale mass concrete block measuring $25\text{ m} \times 10\text{ m} \times 6\text{ m}$ is discretized into 4875 regular hexahedral elements for the simulation. As shown in Fig. 7, three layers of S-shaped cooling pipes are embedded within the block. The pipes are positioned 1 m from the side and bottom surfaces, with a vertical spacing of 2 m between layers. Concrete placement begins at an initial temperature of 16°C . Cooling water at 8°C circulates

through the pipes at a velocity of 0.54 m/s for the first 20 days. A second cooling stage is initiated on the 90th day and continues until the concrete temperature falls below 18°C. The flow direction in the pipes is reversed daily. Temperature is monitored at two points, namely Point A (5.25, 12.5, 1.0) and Point B (6.0, 12.5, 1.0). Material parameters in the simulation are given in [Table 2](#).

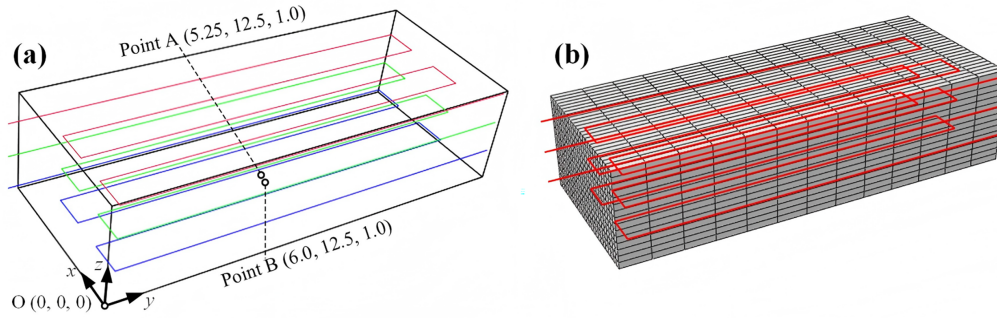


Figure 7: Illustration of mass concrete block test. (a) Water pipe layout; (b) Mass concrete mesh.

4.2 Temperature Distributions with Multi-Pipes

[Fig. 8](#) presents the concrete temperature (NT11) contours on the 8th day. Both the distribution across the central cross-section ([Fig. 8a](#)) and the variation along the pipe axis ([Fig. 8b](#)) exhibit a consistent trend. The temperature initially increases gradually along the cooling water flow direction before decreasing near the pipe outlet. The concrete region adjacent to the water inlet approaches the inlet water temperature, whereas the area near the outlet remains slightly cooler than the central mass of the block. The heat flux nearby inlet is dominated by the heat exchange between concrete and pipe, while the Dufour flux along the pipe is the main component of element heat flux. A comparison between [Fig. 8a,b](#) indicates that the embedded cooling pipes effectively lower the internal concrete temperature, while the water temperature shows a considerable rise along its flow path.

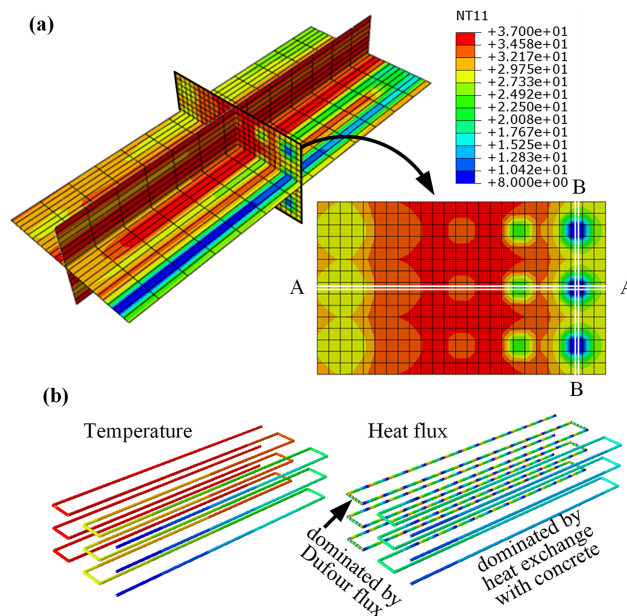


Figure 8: (Continued)

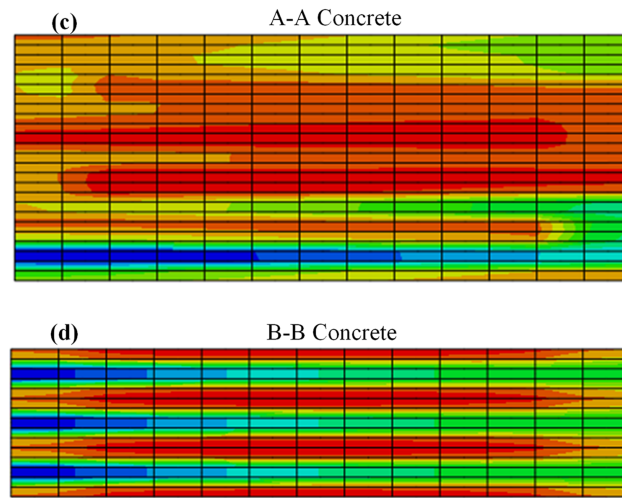


Figure 8: Contours of temperature distribution on the 8th day. (a) Overview; (b) Water pipe temperature and heat flux; (c) Section A-A; (d) Section B-B.

Notably, the temperature at the pipe outlet is slightly higher than the actual water temperature inside the pipe at that location. This discrepancy is primarily attributed to the daily reversal of the flow direction. As depicted in Sections A-A and B-B (Fig. 8c,d), the concrete temperature is lower in the immediate vicinity of the pipe compared to regions farther away. Furthermore, the temperature field exhibits a periodic distribution pattern along the vertical direction of the block, resulting from the uniform vertical spacing of the pipe layers and the adiabatic boundary conditions at the concrete surfaces.

The temperatures at Point A (adjacent to the pipe) and Point B (distant from the pipe) over the entire 133-day cooling period are quantitatively compared in Fig. 9. The concrete temperature first rises due to cement hydration heat. With the activation of pipe cooling, the temperature at Point B increases from 15°C to a peak of 33°C on the 6th day, which is significantly lower than the adiabatic temperature rise of 29°C. Following the peak, the temperature declines gradually as cooling continues. Upon completion of the first cooling stage, the temperature at Point B increases significantly again due to thermal equilibration with Point A, as illustrated in Fig. 9b. The concrete temperature decreases again once the second cooling phase concludes in Fig. 9c. Throughout, Point A cools more rapidly than Point B and shows stronger direct influence of the cooling pipe, because of its closer proximity to the water pipe.

The overall agreement between measured and predicted temperatures confirms the model's accuracy and its capability for simulating full-scale mass concrete structures. Additionally, predictions from three methods, namely the effective pipe method (EPM) [1], the heat-flow coupling method (HFM) [19], and the proposed mesh-independent method (MIM), are compared in Fig. 9a. Both HFM and MIM successfully capture the distinct temperature evolution at Points A and B, owing to their explicit modeling of the pipe water temperature, whereas EPM does not. Compared with the field monitoring data from [19], MIM shows slightly better prediction of both peak and valley temperatures, but its prediction is higher than the experimental data between the two stages of water cooling. This condition indicates that the modeling of mass concrete requires an improvement for considering the material properties variation during hydration process.

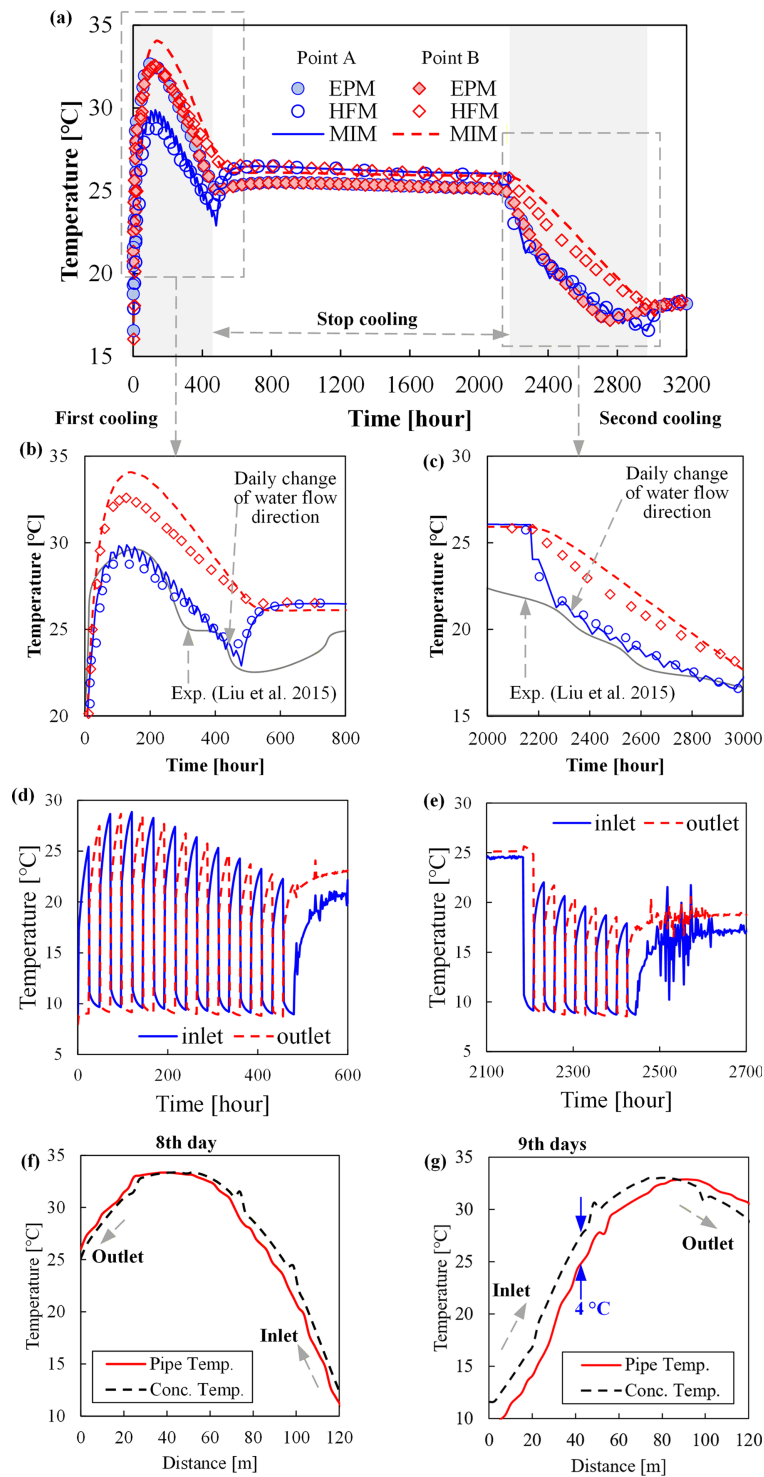


Figure 9: Data of temperature evolution. (a) Temperature evolution over 133 days; (b) Temperature during first stage cooling; (c) Temperature during second stage cooling; (d) Inlet and outlet water temperature during first stage cooling; (e) Inlet and outlet water temperature during second stage cooling; (f) Temperature distribution along pipe at 8th day; (g) Temperature distribution along pipe at 9th day; Notice: EPM-Effective pipe cooling method, HFM-Heat-flow coupling pipe cooling method, MIM-Mesh-Independent pipe cooling method.

The water temperatures at the pipe inlet and outlet ends are also presented in Fig. 9d,e. The water temperature at the pipe inlet is close to 8°C. After the change in flow direction, the temperature on the original outlet side decreases to 8°C. This daily change of water flow direction results in the daily temperature fluctuation in the mass concrete (Fig. 9a). One can also observe that the mass concrete temperatures are higher than the water temperature at the pipe inlet, and their variations exhibit a delay. Fig. 9f,g present the temperature distributions along the pipe path at 6:00 a.m. on days 8 and 9, respectively. Both concrete and pipe water temperatures exhibit a characteristic “high in the middle, low at both ends” profile. This pattern arises primarily from the combined effect of longitudinal heat gain in the flowing water and the daily reversal of flow direction. Consequently, the concrete near both ends of the water pipe path remains consistently cooler. At the flow endpoint, which served as the inlet on the previous day, the concrete temperature remains relatively low. Meanwhile, the pipe water temperature increases continuously along the flow path due to longitudinal heat absorption, eventually exceeding the surrounding concrete temperature and causing a localized reverse heat transfer from the water back to the concrete.

This full 140-day simulation completes within 37 h on a laptop equipped with an 8-thread i7-10875H CPU. This computation speed (time increment) depends on the predefined maximum local temperature change allowed per iteration, as well as on the local temperature increment of the concrete and pipe elements, which is controlled by their LTNE heat exchange.

4.3 Effect of LTNE

Significant differences in thermal conductivity and heat capacity among the water, pipe wall, and concrete, along with rapid heat absorption and temperature rise of water along the flow path, prevent instantaneous thermal equilibrium between the in-pipe water temperature and the adjacent concrete. The dimensionless Biot number represents the heat exchange capability between water in pipe and the thermal conductivity in concrete, which is computed as: $Bi = \beta_p d_p / \lambda_c$. Based on Table 2, the $Bi = 0.15 > 0.1$ which means the thermal resistances of the pipe wall and convective heat transfer further retard heat exchange. The local LTNE state characterized by a sustained and non-negligible temperature difference between water and concrete directly impacts the accuracy of temperature field predictions. At the end of day 8, the LTNE effect produces a temperature difference of 4°C.

The accumulation of thermal strain within the beginning 7 days can be calculated as: $\sigma = \int_0^{7d} \Delta T \alpha(t) E(t) dt$, with age-dependent elastic modulus $E(t) = 30(1 - 0.4e^{-0.34t})$ GPa and linear thermal expansion coefficient $\alpha(t) = 14 \times 10^{-6}(1 + 0.4e^{-11t})/^\circ\text{C}$ [24,25]. This temperature difference of 4°C can induce a thermal tensile stress of approximately 0.11 MPa, which corresponds to about 7.9% of the tensile strength (taken as $2 \text{ MPa} \times 0.7 = 1.4 \text{ MPa}$) [26]. These results underscore the importance of accounting for the LTNE effect in temperature-control design for mass concrete construction and validate the practical need for the proposed mesh-independent water pipe cooling method.

Note that the purely linear elastic stress estimation serves only as a nominal theoretical reference for qualitative comparison, as early-age concrete undergoes significant basic creep and stress relaxation. A more realistic assessment requires a viscoelasticity damage model coupled with the hydro-thermo-chemical behavior at early age.

5 Conclusions

Water pipe cooling is a widely adopted technique for mitigating early-age thermal cracking in mass concrete by controlling its temperature field. However, conventional simulation methods often neglect the local thermal non-equilibrium (LTNE) effect at the concrete-pipe interface and are hampered by computational inefficiency, as they typically require complete re-meshing whenever the pipe layout is modified. To

address these dual challenges, this study proposes a novel mesh-independent simulation method based on spatial topological mapping. This approach effectively decouples the pipe network discretization from the concrete mesh, achieving an optimal balance between computational accuracy and efficiency. Its robustness and general applicability are rigorously validated through a series of numerical case studies. The principal findings of this work are summarized as follows:

1. A novel mesh-independent method for simulating pipe cooling in mass concrete is developed. Its core innovation is the establishment of a spatial topological mapping between the concrete hexahedral solid elements and the pipe lattice elements, which effectively models their conjugate heat transfer without requiring geometric conformity.
2. The method achieves a balance between accuracy and computational efficiency. It retains the precision of conventional heat-flow coupling simulations while approaching the computational speed of simplified functional methods. Validation against experimental data shows a maximum error below 3.2%, thereby validating its computational precision and robustness.
3. The simulation successfully captures the LTNE effect, which is manifested as a distinct temperature difference between the pipe water and the surrounding concrete. This temperature difference, initially reflecting the cooling effect, diminishes along the flow path and eventually reverses due to continual heat absorption by the dynamic process further accentuated by the daily flow reversal. The resulting thermal tensile stress substantially elevates the risk of early-age thermal cracking in the concrete.

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