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Flow rate and leakage-channel geometry govern thermal anomalies in tunnel lining blocks

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Highlights

- (1) Laboratory temperatures are compared with a local lining heat-transfer model.
- (2) Higher flow rates intensify cooling and extend its spatial reach.
- (3) Channel offset redistributes cooling more strongly than rotation in the tested cases.
- (4) Interface-adjacent histories reveal location-dependent cooling rates and amplitudes.

Abstract: Leakage-induced thermal anomalies depend on water inflow and channel geometry, complicating interpretation of tunnel-lining temperatures. Laboratory tests and a three-dimensional fracture-flow and heat-transfer model examined these effects in a simplified two-block lining. Measured and simulated temperatures were compared over 6 h, with predictions extended to 24 h. For 30 temperature histories, root mean square errors were 0.226–0.952 °C and mean absolute percentage errors were 1.126–4.508%, although temporal correlations varied by location. One-factor analyses of 45 monitoring points showed that increasing flow from 10 to 200 mL min⁻¹ intensified cooling and extended the low-temperature region, but produced diminishing reductions near the inlet. Increasing the offset between upper and lower channels redistributed cooling laterally and caused non-monotonic responses at some locations. Rotating the lower channel about the vertical axis had comparatively little effect. Rapid near-channel cooling coexisted with delayed responses elsewhere, indicating no single stabilization time for the monitoring section. These findings support location-specific interpretation

of internal thermal responses, but surface thermography and quantitative leakage estimation require further validation.

Keywords: tunnel lining; water leakage; channel offset; channel rotation; fracture flow; transient heat transfer

0 Introduction

Water leakage remains one of the most persistent serviceability and durability problems in underground tunnels. Once leakage pathways are formed in or behind the lining, seepage water can accelerate material degradation, modify local stress transfer, induce erosion or void growth, and create visible defects that are difficult to interpret from surface appearance alone (Grobelaar, 1994; Pleshko et al., 2024; Sun et al., 2024; Wang et al., 2020; Wang and Li, 2020; Yoo, 2017; Zhang et al., 2022). For drill-and-blast tunnels, where the lining is cast against a heterogeneous and blasting-disturbed rock mass, the leakage problem is particularly difficult because water may enter through discrete fractures, construction joints, local cracks, or imperfect contact zones rather than through a single regular joint. This makes leakage not only a waterproofing problem, but also a coupled transport problem in which flow paths, lining geometry, and boundary temperature jointly determine the thermal signature observed at the lining surface.

The hydraulic boundary conditions of drill-and-blast tunnels are also intrinsically time-dependent. Analytical and numerical studies of tunnel inflow have shown that groundwater supply, drainage condition, fracture connectivity, and excavation disturbance can strongly affect both the magnitude and the spatial concentration of inflow (Liu et al., 2020; Nikvar Hassani et al., 2016; Sedghi and Zhan, 2021; Su et al., 2017; Zhu et al., 2023). At the same time, blasting can damage the surrounding rock and alter the excavation damaged zone, thereby changing the permeability structure adjacent to the lining (Rehman et al., 2024; Yang et al., 2015). Consequently, leakage in such tunnels should be understood as the surface expression of a three-dimensional seepage system rather than as an isolated wet mark. A detection method that aims to identify leakage at an early stage must therefore be able to connect observable anomalies on the lining surface with the hidden leakage-channel morphology and seepage intensity behind them.

Temperature is a promising bridge between hidden seepage and observable surface response because leakage water transports heat by advection while the lining and

surrounding rock respond through conduction and convection. Previous studies on cold-region tunnels, water-bearing tunnels, and tunnel-lining heat exchangers have demonstrated that groundwater seepage and ventilation can substantially reshape the temperature field around tunnel structures (Cao et al., 2020; Chen et al., 2024; Cuifeng and Menglong, 2018; Ji et al., 2024; Wang et al., 2024; Zhang et al., 2017, 2016). These studies provide an important physical basis for interpreting lining temperature anomalies, but most of them focus on global tunnel thermal environments or energy-utilization systems. The local problem considered here is more specific: leakage through narrow cracks or leakage channels produces a low-temperature zone whose amplitude, footprint, spatial distribution, and temporal development depend on flow rate and leakage-channel geometry.

A rigorous description of this local process requires a coupled fluid-thermal framework. Research on artificial ground freezing and fractured-rock heat transport has shown that seepage velocity, pore or fracture structure, and heat-transfer coefficients can control the movement, distortion, and eventual stabilization of thermal fronts (Alzoubi et al., 2019, 2018; Hou et al., 2022; Qiu et al., 2021; Tavakkoli Osgouei and Akin, 2021; Vitel et al., 2016; Zhang et al., 2021). These advances confirm that advection-dominated heat transfer can be modeled and validated with laboratory measurements, but they do not directly resolve the leakage-detection question in tunnel linings. In particular, the effects of channel offset and rotation on local temperature distributions remain insufficiently quantified, and location-dependent cooling over time has not been systematically linked to leakage-channel parameters.

Recent progress in infrared thermography, multispectral imaging, and learning-based inspection has improved the ability to detect tunnel leakage and water inflow from visual or thermal data (Chen et al., 2021; Han et al., 2022; Kang et al., 2025; H. Wang et al., 2026; K. Wang et al., 2026). However, many detection models remain image-driven: they identify pixels, regions, or defect classes, but they do not necessarily explain why a thermal anomaly takes a particular shape or how that shape changes when the leakage flow rate, channel offset, or channel orientation changes. This weakens the transferability of detection results across tunnel types, environmental conditions, and leakage stages. For non-contact diagnosis to move from phenomenological recognition toward mechanism-based interpretation, the thermal image must be supported by a validated model that links leakage hydraulics, channel geometry, and spatiotemporal

temperature-field evolution.

This study examines how leakage intensity and channel geometry affect thermal responses in a local tunnel-lining region. A three-dimensional fracture-flow and heat-transfer model of two concrete blocks was compared with laboratory measurements under three benchmark conditions. One-factor numerical analyses then varied flow rate, channel offset, and rotation of the lower channel about the vertical axis. Spatial profiles at 45 locations were combined with temperature histories immediately above, at, and below the block interface to distinguish cooling magnitude from response timing. The analysis concerns an internal monitoring section and does not assume that a temperature pattern uniquely identifies the underlying leakage condition. Its purpose is to clarify the simulated thermal sensitivity to these parameters and provide a basis for subsequent surface-level validation.

1 Indoor Model Test of Leakage-Induced Heat Transfer in Tunnel Linings

1.1 Test apparatus

To investigate the heat-transfer mechanism of leakage water in a tunnel, an experimental system for heat transfer induced by lining-crack or construction-joint leakage water was developed in this study. The system uses a test frame as the main structure, and a steel lining box is adopted to simulate a pressurized groundwater environment around the tunnel lining. The test frame is equipped with a computer-controlled insulated enclosure to maintain constant indoor temperature and humidity. A peristaltic pump and a thermostatic water bath constitute the seepage-flow system, providing stable thermal and hydraulic conditions for the concrete lining model (Kang et al., 2025; Tavakkoli Osgouei and Akin, 2021; Zhang et al., 2021).

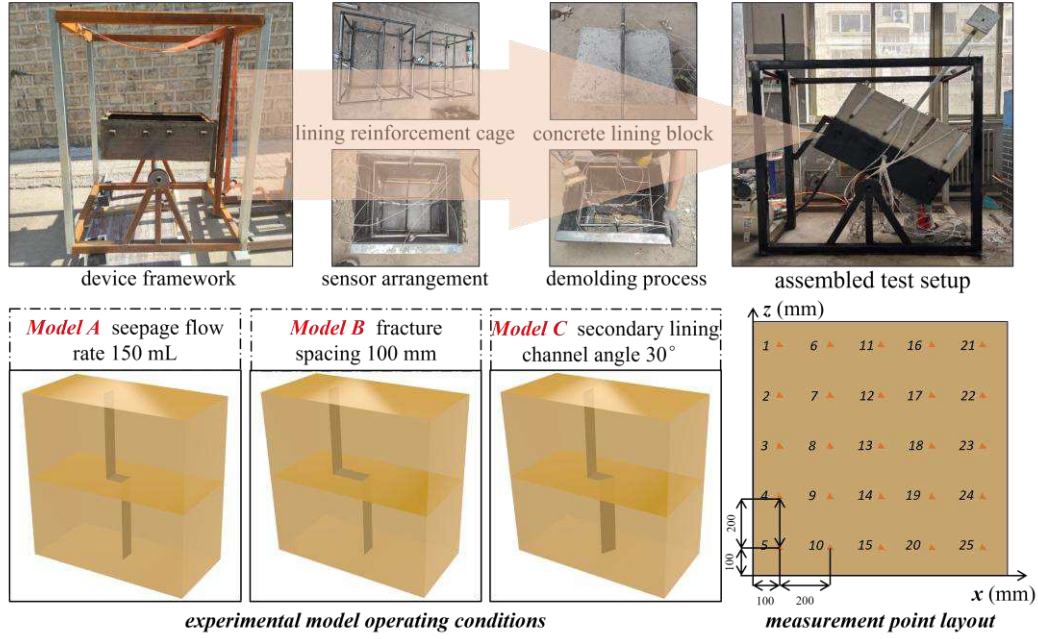


Fig. 1 Experimental system, leakage-channel models, and monitoring-point layout for tunnel lining leakage

1.2 Test specimens and monitoring layout

Fig.1 presents the experimental apparatus, specimen preparation, leakage-channel configurations, and sensor layout. Two C50 concrete blocks reinforced with HPB300 steel cages were used to represent a local region of the secondary lining. Each block measured $1.0 \text{ m} \times 0.5 \text{ m} \times 0.5 \text{ m}$ in the x, y, and z directions, respectively. Stacking the blocks along z gave an overall height of 1.0 m and an interface at $z = 500 \text{ mm}$. Three configurations, Models A–C, were tested under the conditions listed in Table 1. The assembly represents a local leakage region rather than the complete primary support–waterproofing–secondary lining system.

Twenty-five PT1000 sensors were arranged in a 5×5 array on the xz section at $y = 250 \text{ mm}$. Coordinates were referenced to the lower-left corner of this section, with x increasing to the right and z upwards. The five columns were located at $x = 100, 300, 500, 700,$ and 900 mm , with sensors at $z = 900, 700, 500, 300,$ and 100 mm in each column. Experimental point IDs P1–P25 increased down each column and then from left to right (Fig. 1). The sensors were secured to the reinforcement cages using cable ties. Thermal insulation cotton separated the sensors from the steel to reduce conductive interference with the temperature measurements.

1.3 Experimental procedure

- (1) The demountable steel mold was assembled and coated with release agent.

During fabrication of the reinforcement cage, the sensors were accurately arranged using cable ties and thermal insulation cotton;

(2) C50 concrete was poured and fully vibrated. After demolding at 24 h and standard curing for 3 d, the lining-block specimens were moved to the test apparatus using a crane;

(3) Installation was completed by adjusting the leakage-channel configuration, tightening the steel plates with bolts, and sealing the surrounding interfaces to ensure that water migrated only through the designed leakage channel;

(4) Testing began after the thermostatic water bath and peristaltic pump reached stable operation. Temperatures were recorded for 6 h at a sampling interval of 10 s. The temporal comparisons reported below use seven paired values at hourly intervals, including the initial measurement.

1.4 Test conditions

The nominal initial concrete temperature was 20 °C, and the inlet water temperature was 10 °C. Room temperature and relative humidity were maintained at 20 °C and approximately 70%, respectively. The water-filled channels had an aperture of 0.5 mm and contained no infilling. Models A, B, and C were tested at flow rates of 150, 100, and 100 mL/min, respectively, with the channel offsets and rotation angles specified in Table 1. Here, channel offset denotes the horizontal separation between the upper and lower channel centerlines; channel angle denotes rotation of the lower channel about z. The upper channel remained fixed.

Table 1. Test conditions

Test ID	Seepage flow rate (mL/min)	Channel offset (mm)	Channel rotation angle (°)
A	150	200	0
B	100	100	0
C	100	200	30

2 Numerical Model and Case Design

2.1 Basic assumptions

To simplify the calculation and highlight the dominant physical mechanisms, the following assumptions were adopted in the model (Cuifeng and Menglong, 2018; Tavakkoli Osgouei and Akin, 2021):

(1) Material properties are homogeneous within each material and independent of temperature over the investigated range.

(2) Deformation, stress-induced changes in aperture, and associated thermal effects are neglected.

2.2 Model overview

2.2.1 Local lining leakage model

The lining was locally approximated as planar, and the numerical domain reproduced the two-block geometry shown in Fig. 2. The upper channel was fixed at $x = 300$ mm over $z = 500$ – 1000 mm. The lower channel occupied $z = 0$ – 500 mm, with its centerline shifted to $x = 300$ mm + d and its orientation rotated through α about z . The monitoring section remained at $y = 250$ mm. Each original experimental column was densified by inserting one point midway between adjacent sensors, giving nine numerical points per column and 45 points in total. Numerical points were spaced at 100 mm vertically, from $z = 900$ to 100 mm, and the five column positions were unchanged. Numerical IDs P1–P45 increase down each column and then from left to right. These IDs are used in Figs. 2 and 6 – 13 and differ from the 25-point experimental numbering retained in Figs. 1, 3, and 4 and Table 4.

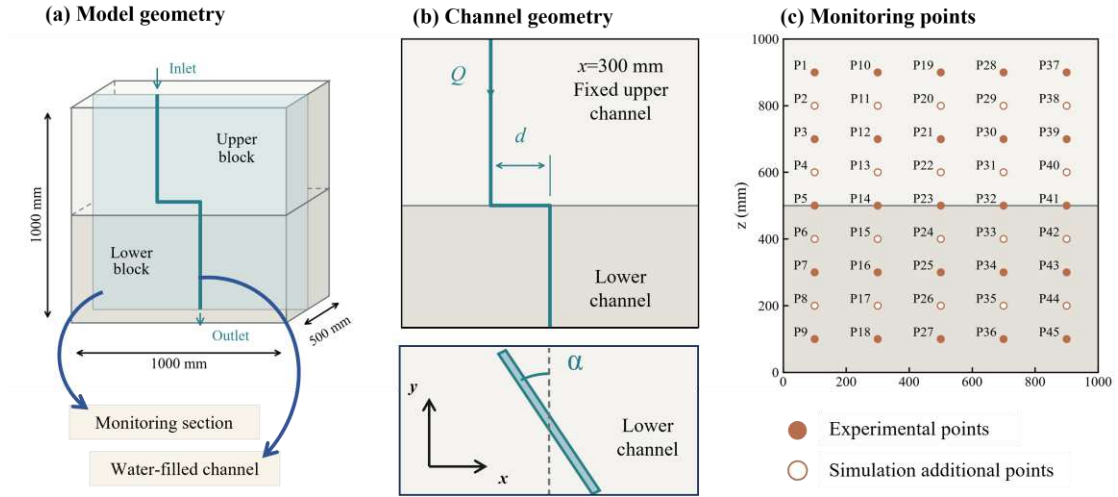


Fig. 2. Numerical geometry, leakage-channel parameters, and the 45-point monitoring array on the xz section at $y = 250$ mm

2.2.2 Material parameters

The main material parameters used in all models are listed in Table 2.

Table 2. Material parameters

Material	Density (kg/m ³)	Thermal conductivity	Specific heat capacity at
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		(W/(m·K))	constant pressure (J/(kg·K))
Water	1000	0.59	4200
Concrete	2500	1.28	970

2.2.3 Fluid–thermal coupling mechanism

Leakage-induced cooling was simulated in COMSOL Multiphysics by coupling the Fracture Flow and Heat Transfer in Solids and Fluids interfaces (Alzoubi et al., 2019; Chen et al., 2024; Zhang et al., 2021). A Darcy-type fracture formulation represented flow through the water-filled channel, with aperture $b = 0.5$ mm and channel width $w = 100$ mm. The smooth parallel-plate approximation gave an intrinsic permeability $k = b^2/12 = 2.083 \times 10^{-8}$ m²; fracture porosity was set to unity to represent the absence of infilling. Water viscosity was 1.002×10^{-3} Pa s. Heat conduction was calculated in the concrete, while the fracture heat-transfer feature accounted for conduction and advective transport within the channel. The fracture-flow velocity was supplied to the thermal equation as the advective velocity. With temperature-independent flow properties, this coupling transfers the flow solution to the thermal problem without thermal feedback on the flow field.

2.2.4 Boundary conditions

The concrete and channel water were initialized at 20 °C, and the channel inlet was maintained at 10 °C. A convective heat-flux condition was imposed on the external top surface of the block assembly at $z = 1000$ mm, with an ambient temperature of 20 °C and a heat-transfer coefficient of $2 \text{ W m}^{-2} \text{ K}^{-1}$. The remaining external concrete surfaces were thermally insulated. At the channel outlet, advective heat transport was retained and conductive heat flux was set to zero.

Water entered through the upper channel at $z = 1000$ mm and exited through the lower channel at $z = 0$. A prescribed normal inlet velocity $U = Q/(bw)$ imposed the selected volumetric flow rate, while outlet gauge pressure was set to zero. Gravity acted in the negative z direction. The upper channel position and all material and thermal parameters were held constant across the numerical cases; only the designated flow rate, lower-channel offset, or lower-channel rotation angle was varied.

2.3 Working-condition design

One-factor analyses were used to separate the effects of flow rate, channel offset, and rotation angle (Table 3). Flow rates of 10, 20, 40, 60, 100, 150, and 200 mL/min were compared at $\alpha = 0^\circ$, with $d = 200$ mm for the spatial analysis and $d = 400$ mm for

the transient analysis. Geometry comparisons used $Q = 100$ mL/min: offsets ranged from 0 to 400 mm at $\alpha = 0^\circ$, and rotation angles were 0° , 30° , and 60° . The angle series used $d = 200$ mm for spatial profiles and $d = 400$ mm for time histories. The offset cases were shared by both analyses. Spatial fields were evaluated at 24 h, and transient histories covered 0–24 h.

Table 3. Working-condition factors

Case ID	Investigated parameter	Q (mL/min)	d (mm)	α ($^\circ$)
SQ01–SQ07	Seepage flow rate	10, 20, 40, 60, 100, 150, 200	200	0
SD01–SD05	Channel offset	100	0, 100, 200, 300, 400	0
SA01–SA03	Channel angle	100	200	0, 30, 60

Note: All cases use $b = 0.5$ mm and the boundary conditions in Section 2.2.4.

3 Experimental Results and Simulation Validation

3.1 Validation indicators and evaluation criteria

Model performance was evaluated against measured spatial temperatures and temperature histories (Chen et al., 2024; Ji et al., 2024, 2023; Liu et al., 2023). At the 25 experimental locations, relative error was defined as $RE = 100|T_s - T_e|/|T_e|$, where T_s and T_e denote simulated and measured temperatures. The discrete measurements were also used to assess whether the simulated section reproduced the principal spatial contrasts in cooling. They do not provide an independent measurement of the complete temperature field.

Temporal agreement was assessed using the root mean square error (RMSE), mean absolute percentage error (MAPE), and squared Pearson correlation coefficient, denoted R^2 . Each metric was calculated separately for each monitoring point using seven paired temperatures at 0, 1, 2, 3, 4, 5, and 6 h. Simulated values were extracted at these measurement times without temporal interpolation. RMSE quantified absolute temperature error, whereas MAPE expressed absolute error relative to the measured temperature in degrees Celsius. R^2 quantified linear association between the paired temperature histories and was interpreted alongside the error metrics, because correlation alone does not establish agreement in magnitude.

3.2 Validation of spatial distribution consistency

Fig. 3 compares simulated and measured temperatures at 25 monitoring locations

on the xz section at $y = 250$ mm for each model. The RE values annotated in the figure ranged from 0.10% to 4.49% for Model A, 0.18% to 5.69% for Model B, and 1.54% to 5.54% for Model C. The largest annotated RE was 5.69%, occurring in Model B at $x = 300$ mm and $z = 500$ mm. The measured and simulated temperatures both showed pronounced spatial heterogeneity, with relatively low temperatures near the channel and higher temperatures towards the right-hand boundary.

In the upper part of the section, all three models exhibited pronounced cooling near $x = 300$ mm. At $x = 500$ mm in the lower part, Models A and C showed substantially lower temperatures than Model B. At $z = 100$ mm along this column, simulated temperatures were 12.72, 18.26, and 13.93 °C for Models A, B, and C, respectively. The corresponding measured temperatures were 13.16, 19.01, and 14.33 °C, preserving the same ordering. These comparisons indicate that the model captured the main spatial contrasts among the tested configurations, including the lateral shift in the cooling pattern.

The pointwise comparisons support the model's representation of the principal spatial temperature contrasts under the tested conditions, although local discrepancies remained. The background contours in Fig. 3 represent simulated fields; the experimental evidence consists of discrete temperature measurements at the marked locations. Accordingly, agreement at these locations does not independently establish the full extent of the cooling zone, validate the velocity field, or identify a unique heat-transfer mechanism.

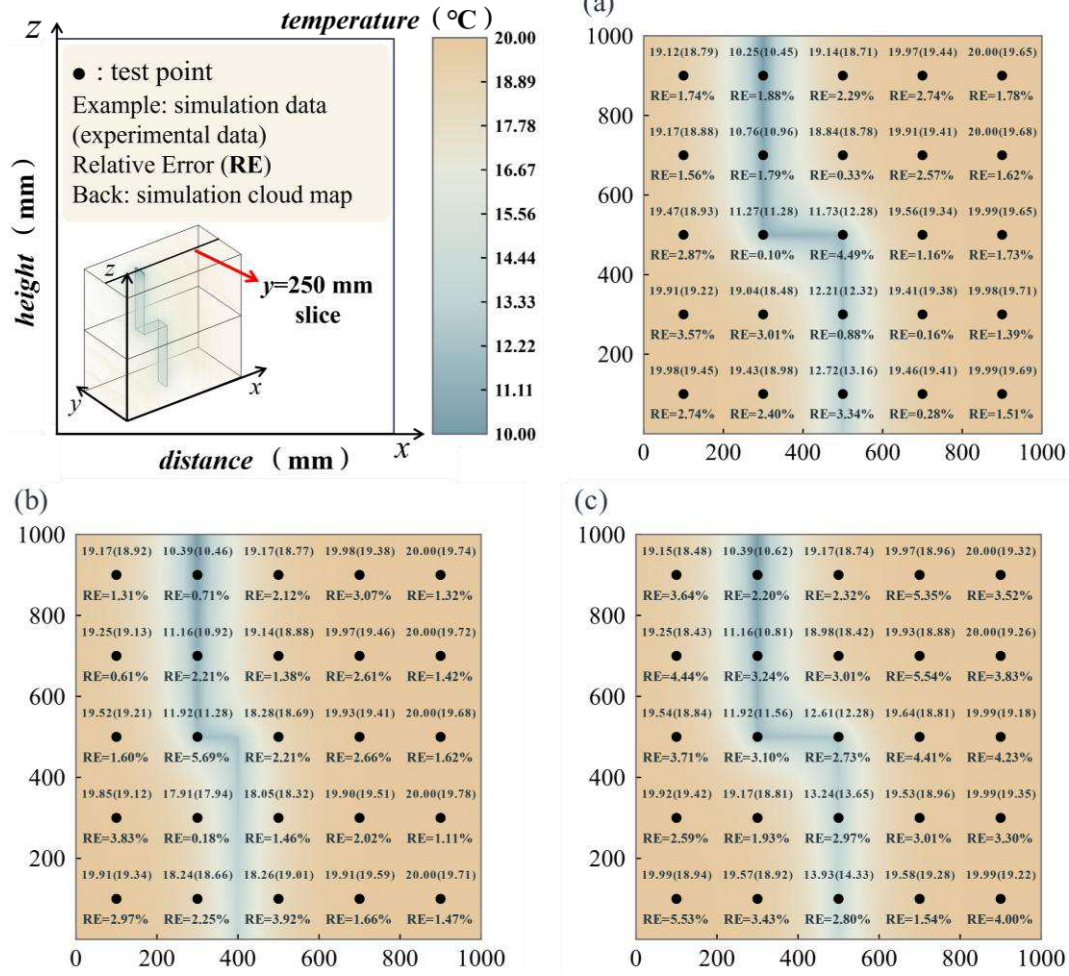


Fig. 3. Simulated temperature fields and paired simulated-measured temperatures at 25 experimental locations after 6 h on the section $y = 250$ mm

3.3 Validation of trend evolution

Fig. 4 compares simulated and measured temperature histories over 0–6 h at ten selected experimental locations in each model. The points were selected by ranking the simulated temperature decrease between 0 and 6 h across the 25 experimental positions. Their coordinates are shown alongside the corresponding histories. Continuous simulation curves are compared with seven hourly measurements at each point. P6–P8 show pronounced initial cooling, whereas several other locations exhibit smaller or more gradual temperature changes. The simulations reproduce the main early cooling responses, although some later measurements fluctuate around the simulated trajectories and correspondence is weaker at several locations with small simulated changes.

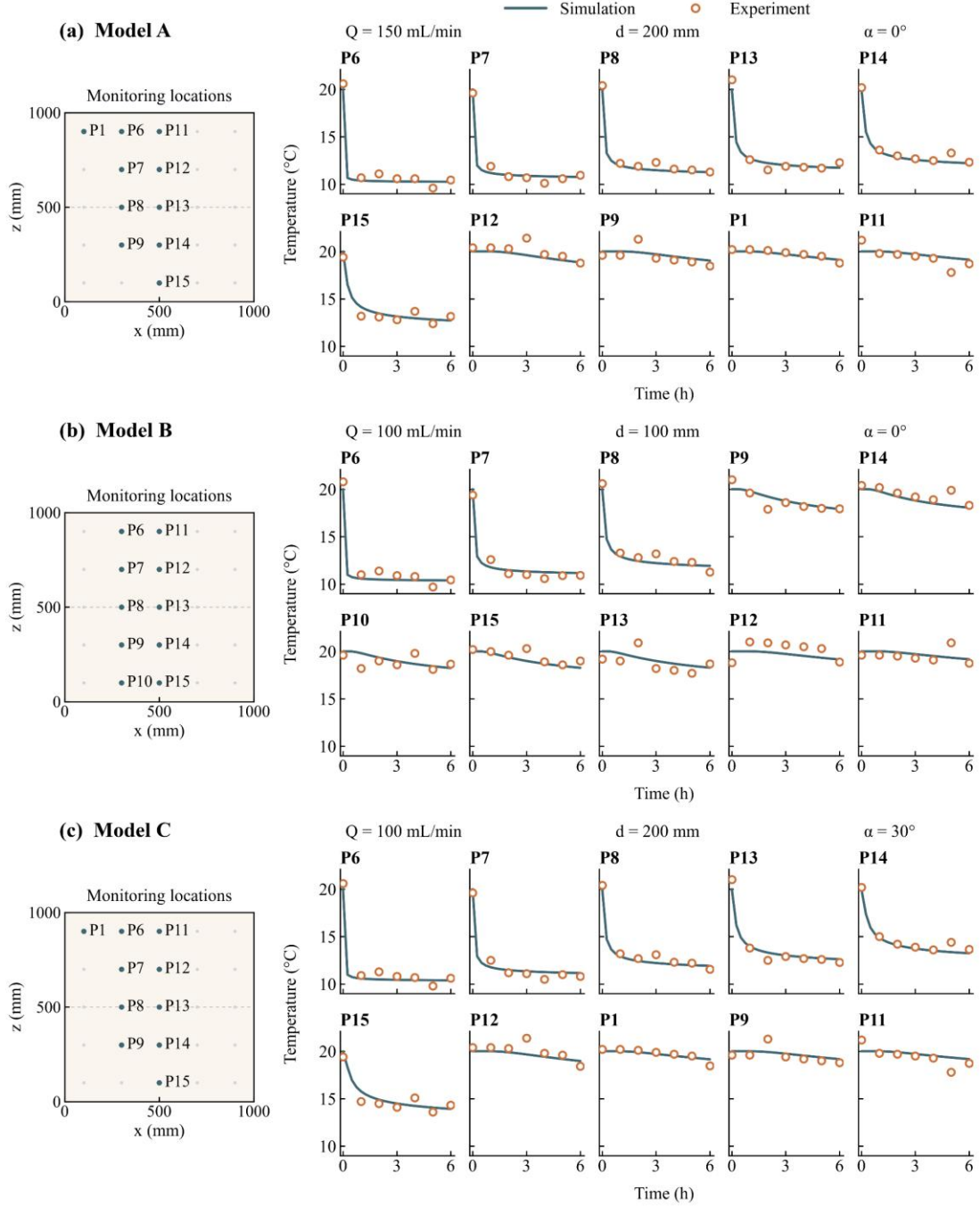


Fig. 4 Simulated and measured temperature histories over 0–6 h for Models A–C

Table 4 quantifies these comparisons. Across the 30 histories, RMSE ranged from 0.226 to 0.952 °C and MAPE from 1.126% to 4.508%. The squared Pearson correlation coefficient ranged from less than 0.001 to 0.994, with 16 of the 30 values exceeding 0.85. Thus, relatively modest absolute temperature discrepancies coexisted with substantial variation in temporal correlation. Model B at P12 had the largest RMSE and MAPE, whereas several strongly cooling points showed high correlation. The results support the principal temperature response under the tested conditions but do not

indicate uniformly high temporal agreement at all selected locations.

Table 4. Pointwise comparison of measured and simulated temperature histories

Model	Point	RMSE (°C)	R^2	MAPE (%)
A	P6	0.500	0.987	3.951
	P7	0.439	0.982	3.180
	P8	0.388	0.994	2.355
	P13	0.516	0.987	2.691
	P14	0.404	0.987	1.958
	P15	0.591	0.950	3.995
	P12	0.760	0.548	2.689
	P9	0.652	0.498	2.774
	P1	0.226	0.910	1.126
	P11	0.761	0.671	2.920
	P6	0.599	0.984	4.482
B	P7	0.518	0.977	3.896
	P8	0.563	0.977	3.838
	P9	0.641	0.676	2.291
	P14	0.716	0.624	2.841
	P10	0.808	0.041	3.496
	P15	0.593	0.620	2.176
	P13	0.891	0.270	4.364
	P12	0.952	0.104	4.508
	P11	0.700	0.000	2.853
	P6	0.500	0.988	3.909
	P7	0.472	0.981	3.530
C	P8	0.434	0.986	2.798
	P13	0.514	0.992	2.585
	P14	0.439	0.980	2.088
	P15	0.649	0.910	3.981
	P12	0.766	0.566	3.010
	P1	0.310	0.848	1.339
	P9	0.623	0.415	2.561
	P11	0.772	0.662	2.986

3.4 Interpretation and limitations of the validation

The comparisons support the model's representation of the principal cooling response at strongly responding monitoring points, while revealing weaker temporal correspondence at several other locations. The relatively high correlations at strongly responding points include the large initial temperature decrease and do not establish equivalent accuracy throughout the subsequent cooling period. Accordingly, the subsequent single-factor analyses are interpreted as predictions conditional on the tested model geometry, boundary conditions, and material properties. Temperature agreement alone does not independently validate the velocity field or isolate the contributions of individual heat-transfer mechanisms.

The experimental comparison covers the first 6 h of leakage. Numerical calculations to 24 h were used to examine later temperature development and changes in cooling rate. Results after 6 h are predictions beyond the experimental comparison window and do not establish experimentally verified late-time equilibrium.

4 Spatial Distribution Characteristics of the Lining Temperature Field

Leakage-induced cooling reflects heat transport by water within the channel and heat conduction through the surrounding concrete. The resulting temperature pattern therefore depends on both seepage flow rate and channel geometry. Using the numerical model assessed in Section 3, this section examines how flow rate, channel offset, and channel rotation angle affect the extent, position, and asymmetry of the cooling zone. The comparisons concern the simulated temperature field on the selected monitoring section after 24 h of leakage.

4.1 Effect of seepage flow rate on the spatial temperature distribution

Seven flow rates, $Q = 10, 20, 40, 60, 100, 150,$ and 200 mL/min , were compared at $d = 200 \text{ mm}$ and $\alpha = 0^\circ$. The initial concrete temperature and inlet water temperature were 20 and 10°C , respectively. Fig.5 shows simulated temperature fields on the section $y = 250 \text{ mm}$ at 24 h.

At the lower flow rates, cooling is concentrated towards the upper channel and inlet region. Increasing flow rate extends the low-temperature region along the offset channel and into the lower block. The resulting contours show greater cooling around the horizontal connection and lower channel, while locations farther from the channel remain warmer. These changes indicate a larger spatial reach of cooling over the investigated flow range.

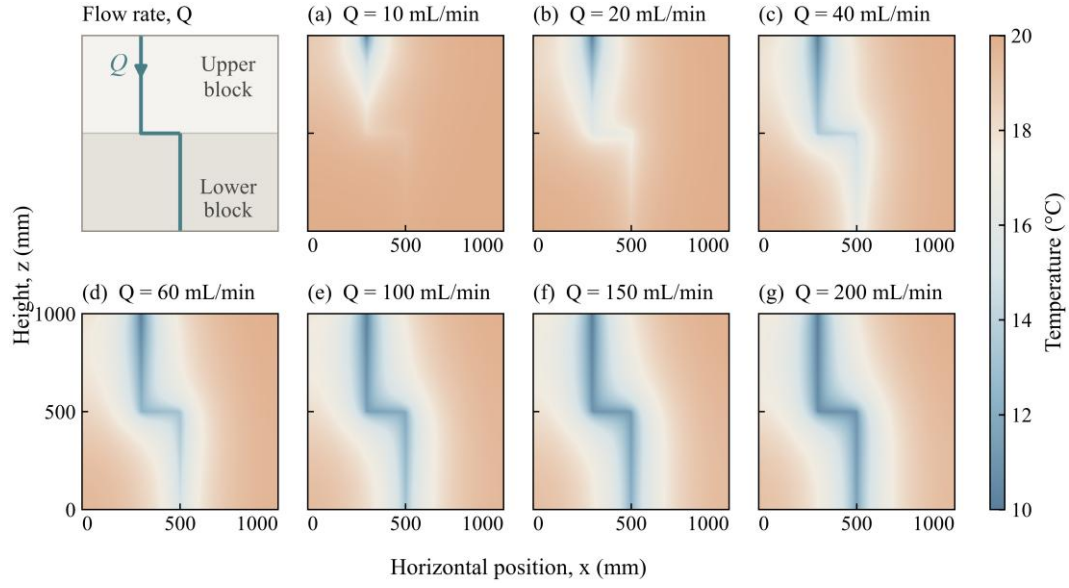


Fig. 5. Simulated temperature fields at 24 h under different flow rates

The five vertical profiles in Fig. 6 quantify this spatially heterogeneous response. At P10 ($x = 300$ mm, $z = 900$ mm), temperature decreases from 13.48 °C at 10 mL/min to 10.14 °C at 200 mL/min. At the interface point P23 ($x = 500$ mm, $z = 500$ mm), the corresponding temperatures are 19.12 and 10.91 °C. Cooling also strengthens along the lower channel: at P27 ($x = 500$ mm, $z = 100$ mm), temperature falls from 19.79 to 11.46 °C across the same flow range. In contrast, the outermost column at $x = 900$ mm remains relatively warm. Flow rate therefore changes both the magnitude and spatial distribution of cooling.

A higher flow rate supplies more cold water per unit time and can sustain cooling farther along the channel. This interpretation is consistent with the broader low-temperature zones in Figs. 5 and 6. At several locations, however, the temperature differences between the higher-flow cases become smaller, suggesting a diminishing local cooling response as temperatures approach the inlet water temperature. The extent and continuity of the cooling zone therefore provide useful descriptors of flow-rate effects within this model. The discrete cases considered here do not define a universal transition flow rate or establish the relative contributions of advection and conduction.

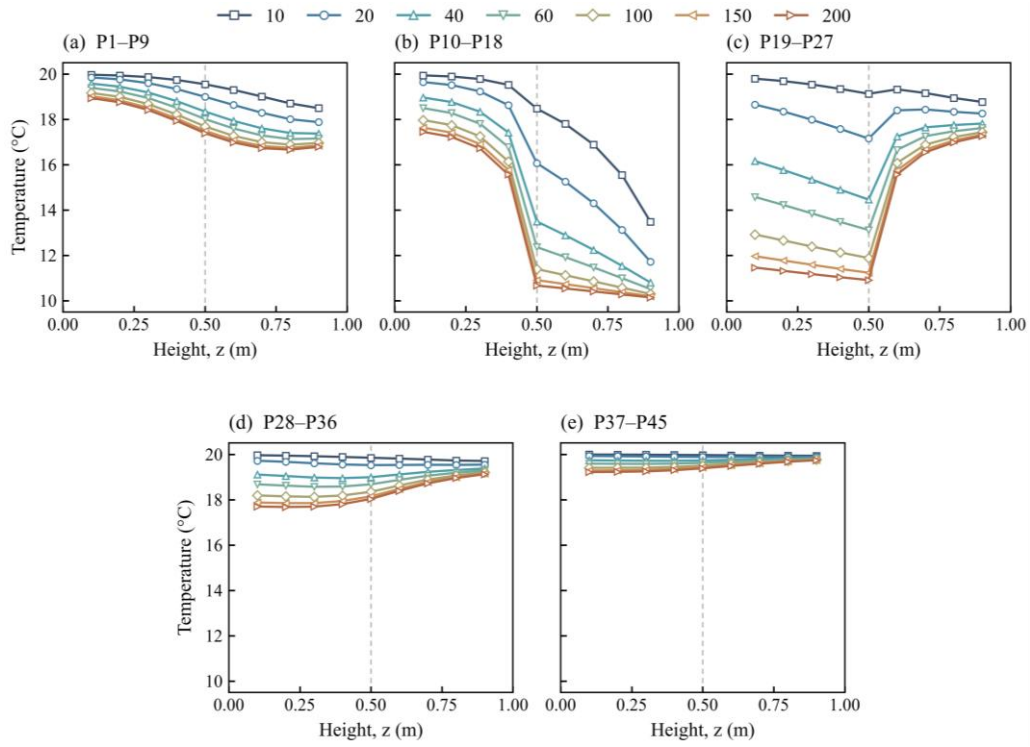


Fig. 6. Vertical temperature profiles at 24 h under different flow rates

4.2 Effect of channel offset on the spatial temperature distribution

Five offsets, $d = 0, 100, 200, 300,$ and 400 mm, were compared at $Q = 100$ mL/min and $\alpha = 0^\circ$ (Fig. 7). The upper channel remained fixed at $x = 300$ mm, while the lower channel shifted to $x = 300$ mm + d . At zero offset, cooling forms a predominantly vertical band around the aligned channels. Increasing d extends the connection along the block interface and shifts the lower cooling region to the right, producing an asymmetric section.

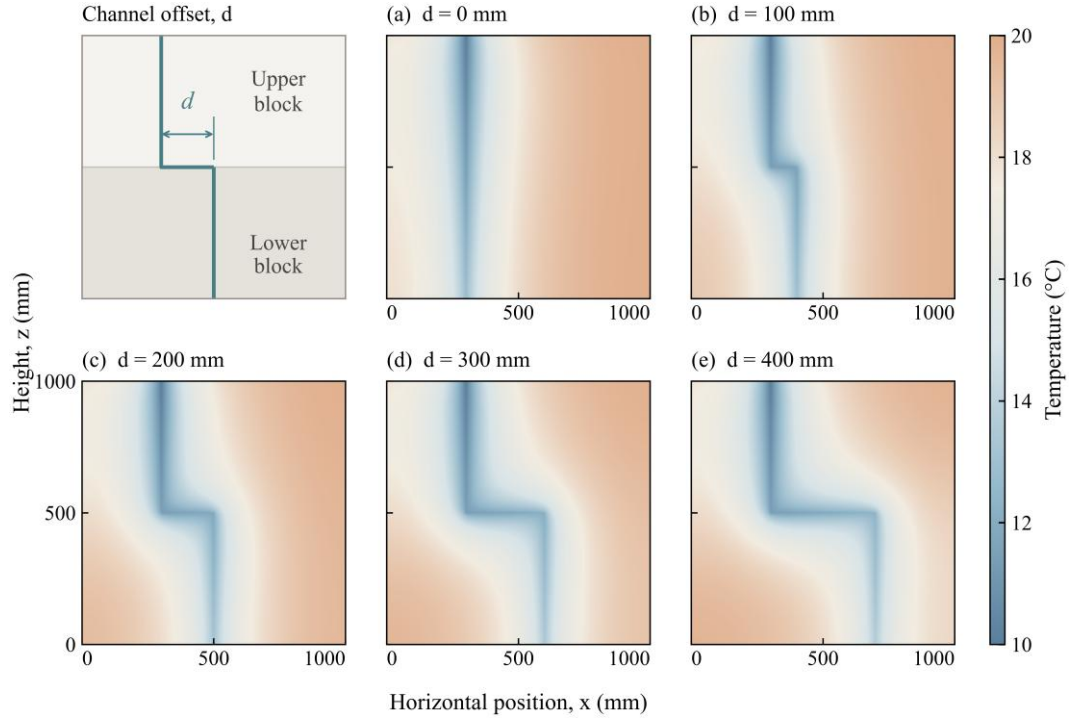


Fig. 7. Simulated temperature fields at 24 h under different channel offsets

The profiles in Fig. 8 show that the offset effect is strongest where the lower channel changes position relative to the monitoring array. At P18 ($x = 300$ mm, $z = 100$ mm), temperature rises from 12.57 to 19.13 °C as d increases from 0 to 400 mm. At P36 ($x = 700$ mm, $z = 100$ mm), it instead falls from 19.45 to 13.38 °C. The intermediate column shows a non-monotonic response: P27 reaches its lowest temperature, 12.92 °C, at $d = 200$ mm, compared with approximately 18 °C at either end of the offset range. In the upper channel, P10 changes by less than 0.01 °C. These contrasts reflect redistribution of cooling around a fixed upper channel and a displaced lower channel.

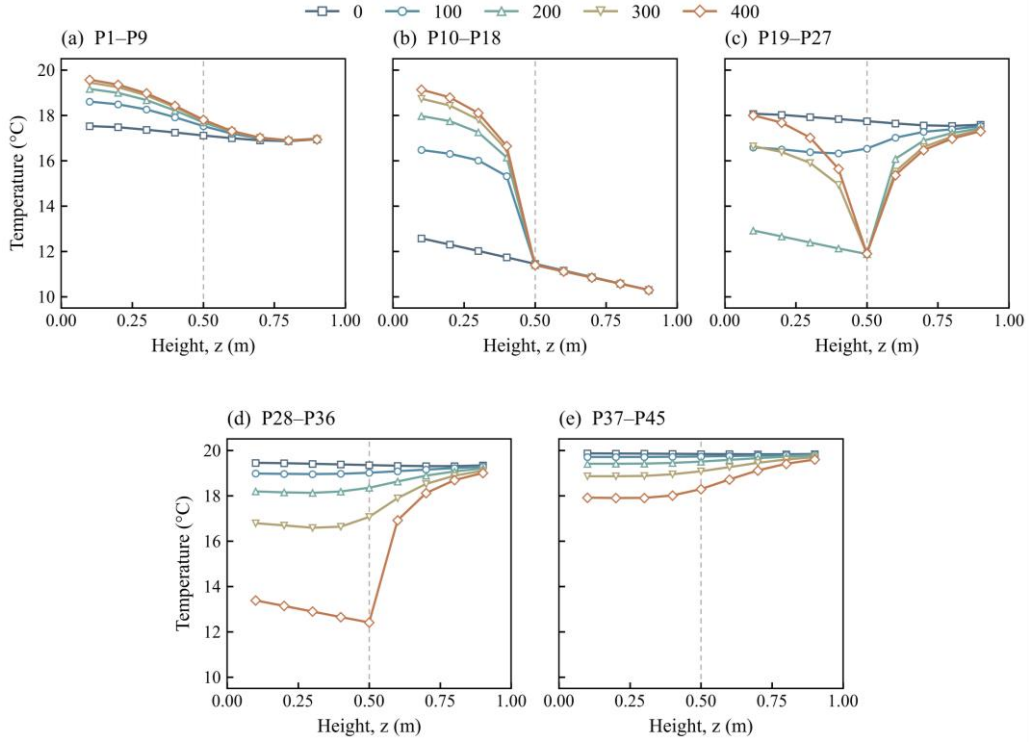


Fig. 8. Vertical temperature profiles at 24 h for the five channel offsets

These contrasting responses are consistent with changes in the position of the leakage path relative to the monitoring points. Adjusting d redistributes the channel geometry between the two blocks, bringing some locations closer to the cooling zone while moving others farther from it. The principal effect is therefore a redistribution of local heat exchange. A larger offset does not necessarily produce a larger temperature decrease at every location.

Taken together, Fig. 7 and 8 show that channel offset affects both the coverage and asymmetry of the simulated thermal anomaly. These spatial features complement cooling magnitude when interpreting the effect of channel geometry. Their use to estimate an unknown offset would require additional assessment of sensitivity to boundary conditions and other geometric configurations.

4.3 Effect of channel rotation on the spatial temperature distribution

Lower-channel rotation angles $\alpha = 0^\circ$, 30° , and 60° were compared at $Q = 100$ mL/min and $d = 200$ mm. Rotation was applied about z , with the upper channel and the lower-channel center position unchanged. The temperature fields at 24 h are closely similar on the common 10–20 °C scale (Fig. 9). The present results therefore indicate a comparatively weak change in the monitored section, rather than a pronounced lateral displacement of the cooling zone.

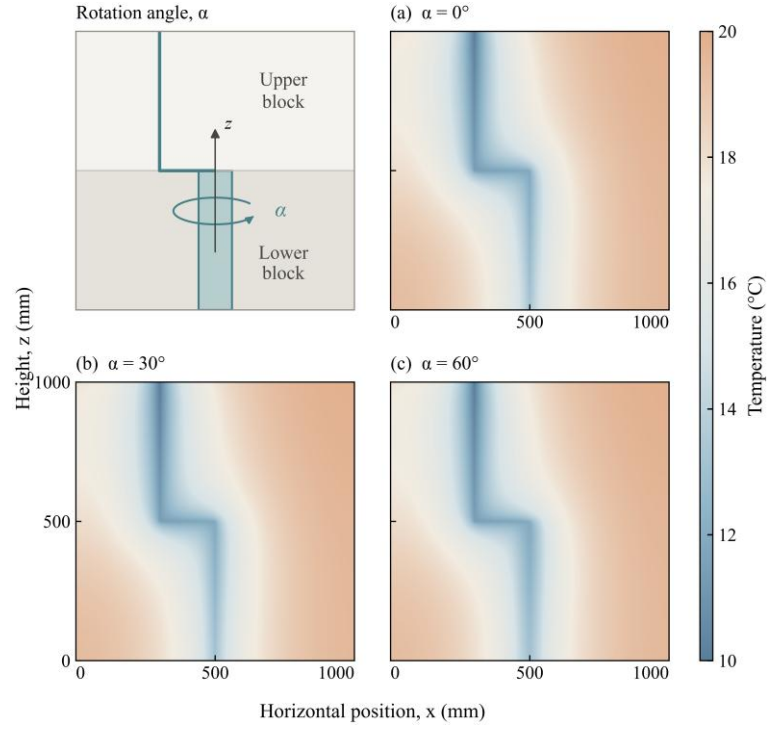


Fig. 9. Simulated temperature fields at 24 h under different lower-channel rotation angles

The enlarged views in Fig. 10 resolve the small differences among the profiles. The largest temperature spread across the three angles among the 45 points is approximately 0.15 °C at P22 ($x = 500$ mm, $z = 600$ mm), where temperature increases from 16.08 °C at 0° to 16.23 °C at 60°. Maximum spreads within the other four columns are below 0.05 °C. The sign is location dependent: rotation slightly raises temperature at P22 but lowers it at P36. These differences are much smaller than those produced by varying flow rate or offset in the corresponding analyses.

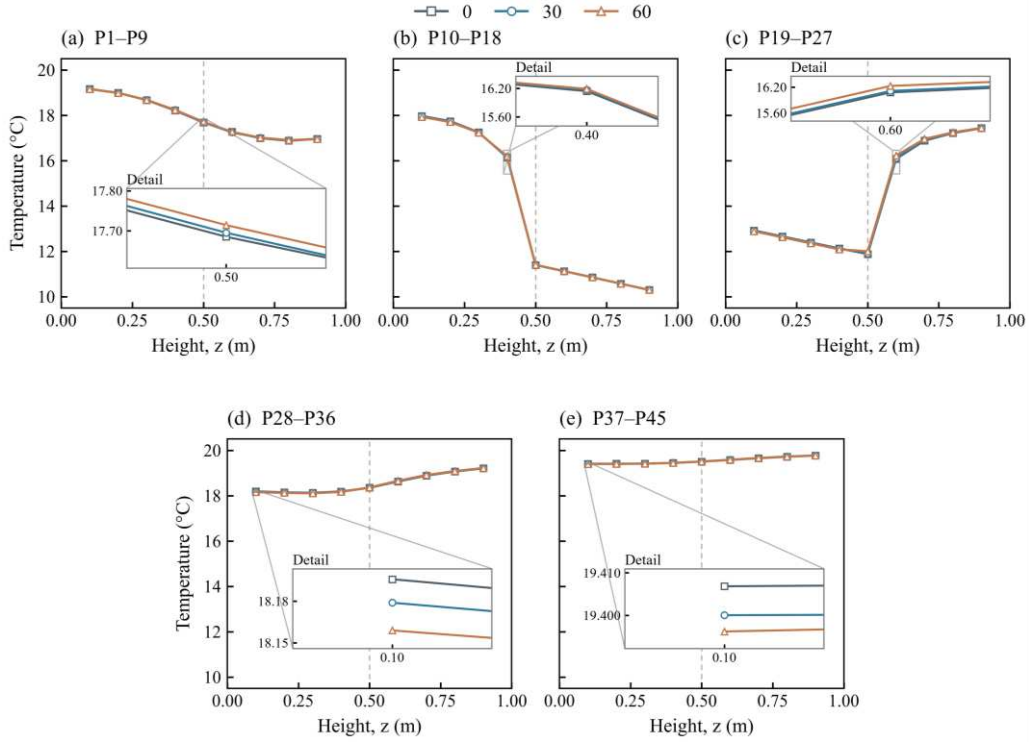


Fig. 10. Vertical temperature profiles at 24 h for the three rotation angles

Rotation about z changes the lower channel orientation in the xy plane while preserving its vertical extent and center position. Consequently, the central xz section can retain a similar cooling pattern even though the three-dimensional channel geometry changes. The small profile differences are consistent with a change in heat exchange around the rotated channel, but the temperature plots alone do not isolate its transport contributions.

For these configurations and this observation section, rotation is a weaker thermal discriminator than channel offset. The enlarged differences should be interpreted as model-simulated sensitivities rather than evidence that the angle could be reliably recovered from temperature measurements. Their robustness requires numerical refinement and experimental resolution appropriate to their small magnitude.

5 Transient Evolution of the Lining Temperature Field

The spatial patterns described in Section 4 develop through temperature responses that vary with both time and location. This section examines how seepage flow rate, channel offset, and channel rotation angle influence cooling magnitude and rate over a 24 h simulation period. Particular attention is given to differences between rapid initial cooling and more delayed responses.

Fifteen numerical points were selected from the array in Fig. 2 to sample three

rows around the block interface. The upper row at $z = 600$ mm contains P4, P13, P22, P31, and P40; the interface row at $z = 500$ mm contains P5, P14, P23, P32, and P41; and the lower row at $z = 400$ mm contains P6, P15, P24, P33, and P42. In each row, x increases from 100 to 900 mm in 200 mm increments. Figures 11–13 retain this arrangement, allowing responses at the same horizontal position to be compared above, at, and below the interface.

5.1 Effect of flow rate on the transient temperature response

Seven flow rates from 10 to 200 mL/min were compared at $d = 400$ mm and $\alpha = 0^\circ$ (Fig. 11). This offset intentionally differs from the 200 mm baseline in the spatial flow-rate analysis. The histories show that increasing inflow generally strengthens cooling, but the response rate depends on position relative to the channel and interface. Points near the upper channel and its interface connection respond rapidly, whereas more distant points cool progressively over a longer period.

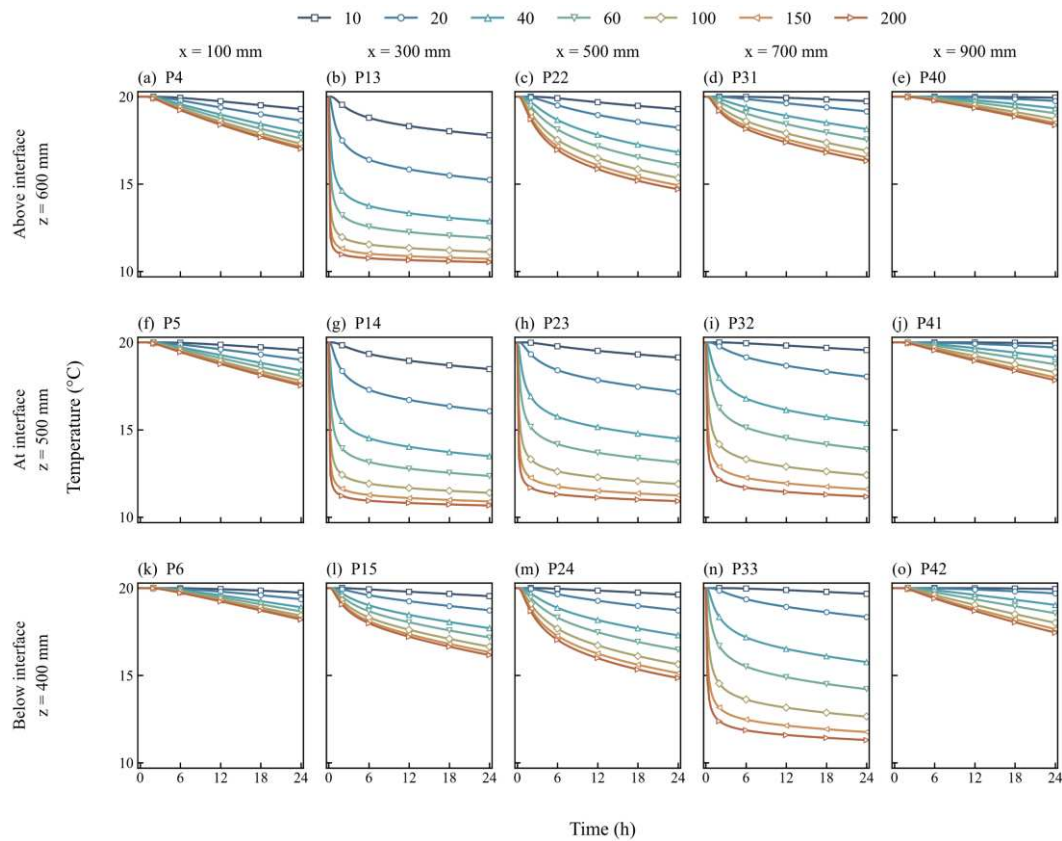


Fig. 11. Temperature histories over 0–24 h for $Q = 10, 20, 40, 60, 100, 150$, and 200 mL/min, with $d = 400$ mm and $\alpha = 0^\circ$

The contrast across the interface is evident at $x = 300$ mm. For $Q = 100$ mL/min, the temperature decreases at P13 and P14 during the first 6 h account for approximately 95% and 94% of their respective 24 h decreases. At P15, immediately below the

interface, this fraction is only about 50%. At the more distant P4, it is approximately 24%. These fractions were calculated as $[T(0)-T(6\text{ h})]/[T(0)-T(24\text{ h})]$ from the exported simulation values. They describe progress relative to the 24 h prediction and are not measures of approach to an independently established equilibrium.

The curves do not support a single sequence of thermal stages at all monitoring locations. At rapidly responding points, the cooling rate decreases as the local temperature falls. Other points continue to cool appreciably later in the simulation. This variation is consistent with heat transport along the leakage channel and subsequent conduction through the concrete, but the temperature histories alone do not resolve the contribution of each process or demonstrate thermal equilibrium.

Flow rate therefore affects both the magnitude and timing of the simulated thermal response. Comparisons across multiple monitoring locations provide more information than a single temperature history because rapid cooling can reflect either stronger inflow or closer thermal coupling to the channel. These effects must be considered together when interpreting temperature-based leakage observations.

5.2 Effect of channel offset on the transient temperature response

Offsets of 0, 100, 200, 300, and 400 mm were compared at $Q = 100\text{ mL/min}$ and $\alpha = 0^\circ$ (Fig. 12). These are the same configurations used for the spatial offset analysis. The fixed upper channel produces closely grouped histories near $x = 300\text{ mm}$ above the interface, whereas the interface and lower-row responses depend more strongly on the position of the lower channel.

The lower row illustrates how cooling follows the shifted channel. At $x = 300\text{ mm}$ (P15), the aligned configuration provides the strongest direct cooling. At $x = 500\text{ mm}$ (P24), the lowest 24 h temperature occurs at $d = 200\text{ mm}$, when the lower channel passes through this column. At $x = 700\text{ mm}$ (P33), cooling is strongest at $d = 400\text{ mm}$. For example, P24 reaches $12.13\text{ }^\circ\text{C}$ at $d = 200\text{ mm}$, compared with $17.83\text{ }^\circ\text{C}$ at zero offset and $15.64\text{ }^\circ\text{C}$ at $d = 400\text{ mm}$. The local response is therefore governed by channel position and need not vary monotonically with offset.

Changing the offset repositions the leakage path relative to fixed monitoring locations. Cooling is enhanced where the thermal influence of the channel becomes stronger and reduced where that influence weakens. Channel offset therefore controls the spatial distribution of response times and cooling magnitudes, rather than imposing a common trend at all points.

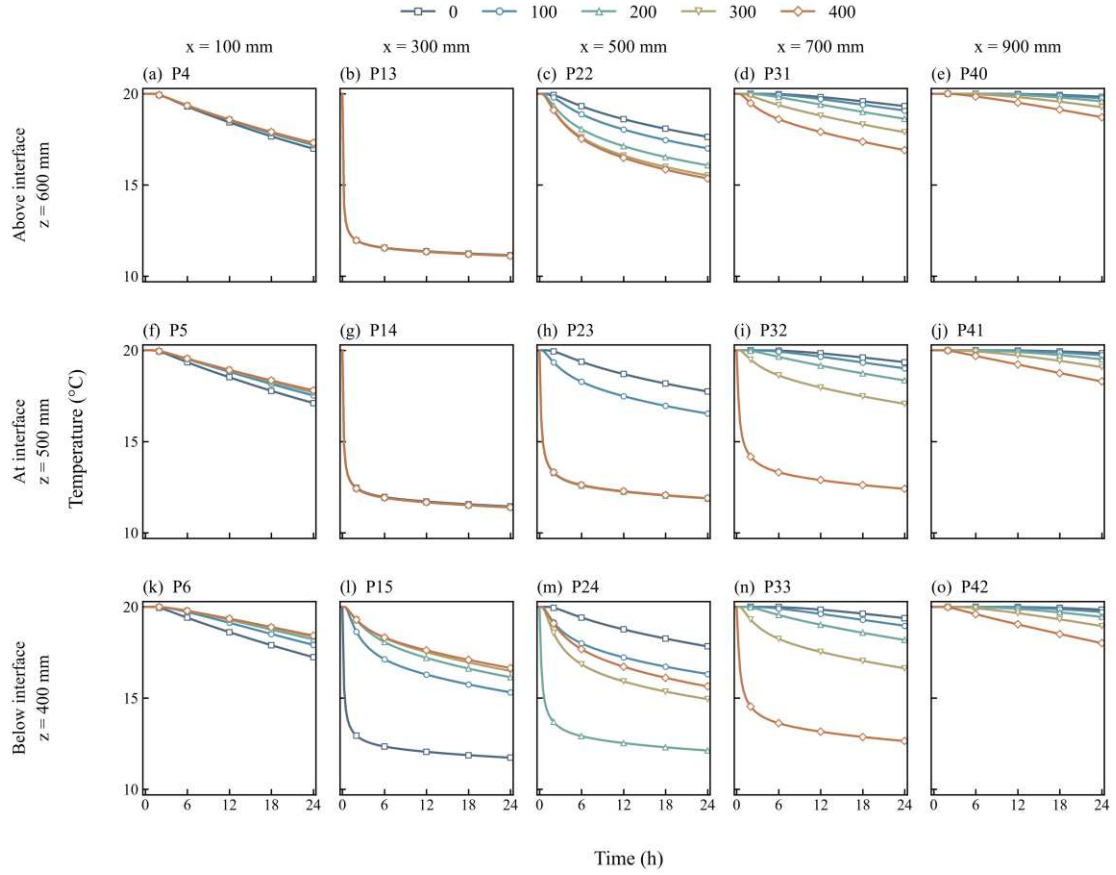


Fig. 12. Temperature histories over 0–24 h for $d = 0, 100, 200, 300$, and 400 mm, with $Q = 100$ mL/min and $\alpha = 0^\circ$

Comparing the three rows distinguishes the relatively stable response near the fixed upper channel from the redistribution of cooling along and below the interface. The interface row samples the horizontal connection, while the lower row is more directly affected by lateral displacement of the lower channel. Joint interpretation of these histories is consequently more informative than the temperature decrease at a single location, although determining an unknown offset would require additional sensitivity analysis.

5.3 Effect of channel rotation angle on the transient temperature response

Angles $\alpha = 0^\circ, 30^\circ$, and 60° were compared at $Q = 100$ mL/min and $d = 400$ mm (Fig. 13). Panel (a) shows the temperature histories at the 15 interface-adjacent points, and panel (b) shows differences relative to the unrotated case, $\Delta T = T_\alpha - T_{0^\circ}$. The absolute histories are closely grouped, so the difference plots are needed to resolve the relatively small angular response.

The angular effect varies with location and time. Across the selected points and saved times, the 60° – 0° difference ranges from approximately -0.43 to $+0.23$ °C; the

30°–0° differences remain within approximately -0.11 to $+0.06$ °C. The largest negative difference occurs at P33 at 0.25 h, indicating slightly stronger early cooling in the 60° case. At 24 h, positive differences of approximately 0.20–0.23 °C occur at P22, P24, and P31. These values indicate small changes superimposed on the main cooling response, rather than a large separation between the absolute histories.

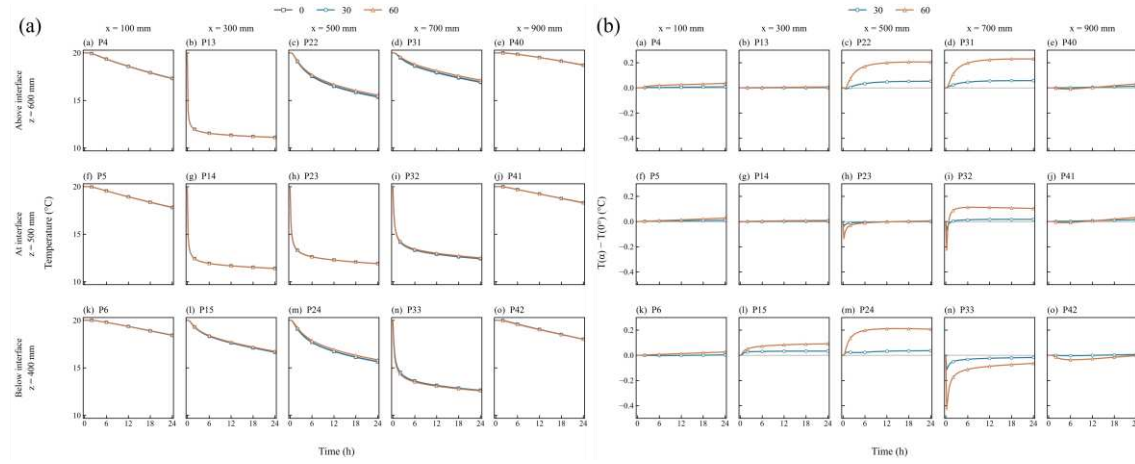


Fig. 13. Influence of lower-channel rotation on temperature evolution at $Q = 100$ mL/min and $d = 400$ mm. (a) Temperature histories for $\alpha = 0^\circ$, 30° , and 60° . (b) Temperature differences relative to $\alpha = 0^\circ$, defined as $\Delta T = T_\alpha - T_0$

Some differences change sign during the calculation. At P32, rotation through 60° initially produces a slightly lower temperature than the unrotated case, but the difference becomes positive and reaches approximately 0.10 °C at 24 h. At P33, the early negative difference decreases in magnitude to approximately -0.06 °C by 24 h. Thus, the final spatial field alone does not describe the complete angular response, even where the absolute temperature curves appear similar.

The spatial and temporal angle analyses use different offsets, 200 and 400 mm, respectively, and should therefore be interpreted within their own reference configurations. Both show modest angular sensitivity on the central section. The difference curves reveal its timing and sign, but do not establish an experimentally resolvable angle signature or a unique relationship between temperature and channel orientation.

5.4 Mechanistic interpretation of leakage-induced thermal anomalies

The simulated responses are consistent with cold water transporting heat along the prescribed channel while conduction distributes the disturbance through the concrete. In the investigated ranges, flow rate strongly affects cooling magnitude and reach, and channel offset changes which locations are directly influenced by the lower channel

and interface connection. Rotation about z has a smaller effect on the central section. The interface-adjacent histories further show that cooling rate depends on both geometry and observation location. These results describe the behavior of the adopted coupled model; they do not independently separate the contributions of advection and conduction or establish a unique inverse relationship between thermal features and leakage parameters.

5.5 Engineering implications and limitations

The model represents a local region using two concrete blocks, rather than the complete primary support–waterproofing–secondary lining system. Its predictions depend on the fixed aperture, idealized water-filled channel, constant material properties, and specified thermal and hydraulic boundaries. Experimental comparisons cover only 6 h, whereas the later results extend to 24 h. In addition, the small angular differences require a dedicated mesh and time-resolution assessment under the present flow conditions before being interpreted as robust quantitative signatures. Longer-duration experiments and surface measurements are needed to assess transferability under variable lining thickness, groundwater temperature, ventilation, and channel connectivity.

6 Conclusions

A three-dimensional fracture-flow and heat-transfer model was evaluated against laboratory measurements and used to investigate leakage-induced cooling in a local tunnel-lining configuration. The main conclusions are as follows:

(1) The simulations captured the main spatial temperature contrasts and transient cooling responses observed in the experiments, with RMSE values of 0.226–0.952 °C across the selected monitoring histories.

(2) Increasing flow rate intensified cooling and extended the low-temperature zone along the leakage channel. The additional cooling near the inlet diminished at higher flow rates as the local temperature approached the inlet water temperature.

(3) Channel offset shifted the cooling zone within the lower block, producing location-dependent and sometimes non-monotonic temperature changes. By comparison, rotation of the lower channel about the vertical axis had a limited effect on the central monitoring section.

(4) Temperature histories above, at, and below the block interface revealed distinct response rates. Rapid cooling near the channel coexisted with delayed cooling in the

surrounding concrete, indicating that spatial temperature patterns and response timing should be considered together when interpreting leakage-induced thermal anomalies.

Author Contributions

Jiabao Wang: Investigation; Data curation; Formal analysis; Visualization; Writing – original draft. Quanyi Xie: Conceptualization; Methodology; Writing – review & editing; Funding acquisition. Xiang Jia: Formal analysis; Visualization. Xiaohan Li: Investigation; Validation. Lizhi Zhou: Methodology; Validation. Jianhong Wang: Project administration. Jian Liu: Conceptualization; Supervision; Funding acquisition; Project administration; Writing – review & editing. All authors reviewed and approved the final version of the manuscript.

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Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Data Availability Statement

The data generated and analyzed during the current study are not publicly available due to ongoing research and project-related restrictions, but may be made available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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