

Thermal analysis for Civil Structural Health Monitoring of Concrete Structure in the Presence of Imprecise Values

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KEY WORDS	ABSTRACT
Thermal Analysis Neelum Jhelum Hydropower Project Heat of Hydration Internal Flow Theory Neutrosophic Analysis	In the construction of massive concrete structures such as dams, bridges, foundations, retaining walls, and nuclear power plant containment structures, temperature control is one of the most critical engineering challenges. This is mainly due to the heat of hydration which is the heat released when cement reacts with water during the hydration process. This creates temperature gradients and tensile stresses that exceed the tensile strength of concrete, causing cracks. Cracks reduce durability, allow water ingress, and can cause long-term structural weaknesses. Engineers mitigate this through material selection, construction practices, and artificial cooling methods, i.e., pipe cooling. A numerical model was created in this work for the thermal analysis of mega concrete structures with pipeline cooling systems, and the robustness was assessed via a neutrosophic approach. Pipe modeling was done using a line element, and for determining the thermal fluctuation of water being used, the internal flow theory was adopted. The projected outcomes were compared with the measurement statistics from the Neelum Jhelum hydropower project's bypass tunnel concrete foundation. The expected outcomes and the site analysis information demonstrated high consistency. Neutrosophic sensitivity analysis also confirms that the modeled coefficients were highly robust.

1. Introduction

It is particularly challenging to predict the temperature history caused by hydration heat in large concrete structures [1]. The issue is caused by the thermal characteristics that change with the passage of time and temperature, as well as other elements that have an impact on the adiabatic temperature increase curve [2]. It proved difficult to analyse a workable solution to the heat absorption issue associated with pipe cooling processes using flowing water [3]. Large quantities of concrete are used to construct the monolithic mass structure of the hydropower projects and dams; it takes much time to attain stability due to the large size and the hydration energy of the cement in the concrete [4]. The changes in the temperature of

the concrete structure are due to an adiabatic process, resulting in the crack that leads to the safety problems and catastrophic damage to the structure [5]. Crack control is the primary factor to be taken into account while designing a mega concrete structure, and the regulation of temperatures is the primary method of fracture mitigation since fluctuations in temperature account for a substantial amount of pavement fractures [6]. After reaching peak ambient temperature, it takes decades for the average temperature to normalize; therefore, it is essential to consider crack prevention while designing such a mega concrete structure [7]. Numerous scholars have investigated the causes of common temperature cracking and the effects of various thermal management systems to stop cracking

over time. Understanding the actual temperature dispersion of the concrete structure lays the foundation for tackling the issue of controlling temperatures and crack mitigation [8]. Thermal monitoring and fracturing containment are the main engineering obstacles encountered during the ahead-of-schedule conceptualization and development period of mass reinforced concrete structures because of absorbing heat and the cooling process conditions, difficult outside environments, and severe underpinning constraints [2]. A collection of anti-cracking techniques has been developed as a consequence of years of industry experience and in-depth research [9]. However, even though the real fluctuation in temperature that the substance experiences can be identified quickly, it is still hard to create a successful mitigation plan. The contemporary globe is beginning to become aware of the concrete structure surveillance mechanism, which entails looking for both major hydroelectric dams' consistent and variable properties [10]. One of the most important aspects that specifically affects the kinematics flexibility of dams made of concrete is the ambient temperature [11]. The naturally occurring weather conditions in the construction of concrete dams are actually explicatory, considering that they affect thermal heating. Resulting in increased burdens on the structural components of the concrete dams, which can have a significant effect on the development and flow of cracks, alongside distractions and changes in the global environment, which could happen as a whole prominence in the environmental temperatures of these hybrid material dams [4]. The everlasting strengthening of dams made of concrete is significantly influenced by climate in the regions of thermal assessment related to non-linear and non-heat flux by conducting a solid substance, considering into account suitable boundary parameters [12]. Dams employ a periodic thermal and stress pattern-based technique predicated on the Finite Element Method (FEM); this technique has truly permitted a far more thorough exploration of the thermal properties of concrete dam structures, both during the initial planning stage of the dam structure and during the specific period of dam monitoring and maintenance [13]. Recent research expanding studies on "Stress Analysis of Concrete Structures" that are negatively impacted by the thermodynamic stress variables, the tenacity of the regular intervals heat flux in a concrete dam, and the estimation of the comparatively common temperature variation in a concrete dam have all focused on this issue [14]. Others have spoken about the thermal field susceptibility study in large buildings and the Arctic concrete dams' temperature concerns [15]. A significant amount of research has already been done recently on the thermal behavior of concrete dams,

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taking into account the results of applying the surrounding circumstances[16]. It includes concrete dam analysis based on intermittent hydrodynamic destruction caused by stationary stress, periodic heat exodus of dams constructed with gravity in regions with low temperatures, and the association between ambient temperature and daily shifts of the structure's durability[17]. While some have studied temperature-induced stresses in concrete dams, others have examined structural cracks in dams[17]; while a previous study has examined the effects of shadowing and ultraviolet radiation [18].

According to earlier investigations, heat transfer impact by water-cooling and internal flow may be considered by identifying specific points of pipeline placements and by decreasing the material component capacity by an amount equal to that of the pipeline. However, this approach is inconvenient since it can be challenging to create the input information for a finite element modelling program, and it does not take the pipe's temperature characteristics into account. We can overcome this problem with the help of a pipe cooling line element.

- The focus of this study was the thermal analysis of mega concrete structures using the heat of hydration and a cooling-pipe system.
- The sensitivity analysis was conducted using a neutrosophic approach to assess the robustness of the modelled coefficients.
- For calculating cooling-water temperature variation, flow theory was used, and pipe modeling was done with the help of a line element.
- The predicted values using formulas and actual measured values from the Neelum Jhelum hydropower project bypass tunnel's concrete were compared to check the reliability of the proposed mechanism.

2. Thermal Conductivity and Specific Heat

Concrete, a multifaceted substance, means that its constituent parts have various temperature characteristics; as a result, several variables, including the kind of substance employed, the quantity proportions of the overall, the hydration heat of the concrete itself, the amount of water in it, and the porosity, impact the thermodynamic attributes of concrete [19]. For thermal conductivity constant flux of heat across an amount of depth of substance across both sides exposed to a specific temperature

differential over the course of a unit period is referred to as the material's coefficient of heat transfer [20]. Concrete's amount of moisture, aggregate type, and unit weight all impact the coefficient; according to JCI and ACI, a typical value of concrete's thermal efficiency is in the range of 2.15-2.51 kcal/m h °C and 1.7-2.53 kcal/m h °C, respectively [21]. For specific heat, a significant consideration for thermal absorption is the particular temperature; it is the quantity of heat needed to alter an identifiable heat throughout a limited temperature range for each unit of mass[22]. Since nearly all concretes have an identical mineralogical makeup, the particular temperature of typical mass concrete hardly differentiates from the kind of material employed [23]. Nevertheless, contingent on its porosity, moisture content, and experimental thermal parameters, the particular temperature of cement paste fluctuates significantly [24]. As a result, these factors also affect how the substance's specific heat varies; according to JCI and ACI, concrete has a typical specific heat value that falls between 0.27 and 0.31 kcal/kg °C and 0.22-0.24 kcal/kg °C [25]. For cooling water and atmospheric convection, the value of the coefficient of atmospheric dispersion, depending on the speed of the wind, determines the amount of thermal energy transferred by the environment[26, 27]; when the wind speed is between 2 and 3 m/s, the coefficient of atmospheric dispersion is between 8 and 11 kcal/m² h/ °C and between 12 and 13 kcal/m² h/ °C[28]. Ohzawa [29, 30] suggested the atmospheric coefficient h_a , as an estimation of wind speed as

$$h_a = 9.60 + 1.12v \quad (1)$$

Whereas wind velocity meter per second is denoted by v , and the coefficient of cooling water convection, as per recommendation of JCI, h_w , will be

$$h_w = 4.75u + 43.0 \quad (2)$$

Whereas cooling water velocity in cm/s is noted by u .

3. Setting Boundary

From the equilibrium equation, consider the following for heat transfer

$$\sum_i \frac{\partial}{\partial t} \left(\frac{\partial T}{\partial i} \right) + q^B = 0 \quad (3)$$

Where q^B is the internal hydration heat, T is the temperature, and the coefficient of heat conductivity is ∂i . Boundary conditions that describe heat transfer

induced must be incorporated in finite element programs developed to take the heat convection effect into account. It is also necessary to maintain a steady temperature at the designated locations regardless of the passage of time. As a result of cooling water convection and atmospheric heat flow

$$q^a = k_{n,a} \frac{\partial}{\partial n} T_{sa} = h_a (T_a - T_{s,a}) \quad (4)$$

and

$$q^w = k_{n,w} \frac{\partial T}{\partial i} T_{sw} = h_w (T_w - T_{s,w}) \quad (5)$$

Where n is the usual path to the dispersion region, and $k_{n,a}$ and $k_{n,w}$ are thermal transmission coefficients of the environment and water-cooling. The borders of the interfaces with the outside environment and cooling water are designated as $T_{s,a}$ and $T_{s,w}$, respectively. The heat diffusion coefficients for the environment and water to cool down are h_a and h_w , respectively. The average temperatures of the environment and cooling water are T_a and T_w ; accordingly, $T_{s,a}$ and $T_{s,w}$ are the atmosphere's actual surface temperatures and the water-cooling's convective boundary surfaces. The requirement for a temperature that remains constant is written as

$$T = T_A^*(x_{i,t}), \quad x_i \in T_A \quad (6)$$

Whereas at a specific time t , the required temperature on specified point is x_i and the suggested temperature rate is T_A^* .

4. Change in Induced Concrete Temperature

The ambient temperature changes resulting from hydration radiation were controlled by pumping water that cools via pipes with relatively thin walls that have been embedded in concrete. The cooling water's capability for absorbing the elevated temperatures generated during the process of hydration of concrete causes the resultant ambient temperature to frequently be much greater than its input temperature. This process is known as "heat transfer by internal flow"[30]. The rate of heat loss from water is determined at every level using the fundamental law of thermal preservation [31, 32], which states that the heat input into the pipe must be exactly equal to the heat the water absorbs as it moves through it[33, 34]. The measurement of the coefficient of water coolant dispersion can be calculated in either of the following methods: a scientific method can be used to resolve the differentiated controlling equation; the other option is to use an algorithm derived from modelling the results of experiments [35, 36]. The following is a

summary of the steps involved in applying the differential governing equation [37-39].

1. Use Reynolds' number to determine if the water flowing through the pipe is laminar or turbulent.
2. Find the hydraulic entrance distance assuming the acceleration of the water's flow is inconsistent.
3. Calculate the thermodynamic entrance distance while the ambient temperature of the flowing water fluctuates.
4. Calculate the hydraulic and temperature admittance distances to get the equilibrium temperature condition.
5. To determine the value of the refrigeration water circulation measurement within the temperature stability range, use the difference in the controlling computation.
6. The differential equation modeling technique has a strong scientific basis, but it is exceptionally difficult to apply to real-world problems[40]. The main obstacle to overcome when using this strategy to investigate concrete foundations with pipe-cooling structures is that the value of the coefficient of cooling water condensation uninterruptedly fluctuates in substantial amplitude throughout the pipe. It is regardless of whether the flowing water is orderly or turbulent. Furthermore, the pipe's cross-sectional layout and roughness of the surface must be taken into consideration throughout the mathematical process. The technique should only be applied if the temperatures of the pipe interfaces where the reinforced concrete outside pipe and flowing water inside pipe contact are stable all throughout time. Consequently, the empirically obtained algorithm according to equation 2 was employed in the present study to compute the water-cooling condensation efficiency. The environmentally friendly technique was employed to determine the level of the coolant water at all the points, as illustrated in Figure 1, presuming that the threshold for the index of cool convection of water has been determined.

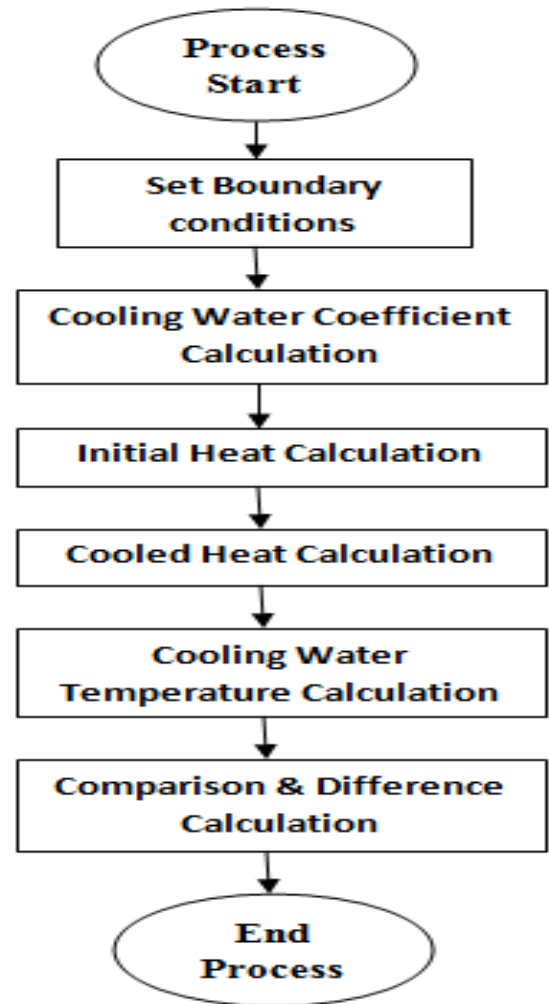


Fig. 1. Flow Chart to Determine the Level of Coolant Water at all Points

The logic-based representation of the environmental maintenance hypothesis, as mentioned in the following Figure 2, is used to further illustrate the structure of the system.

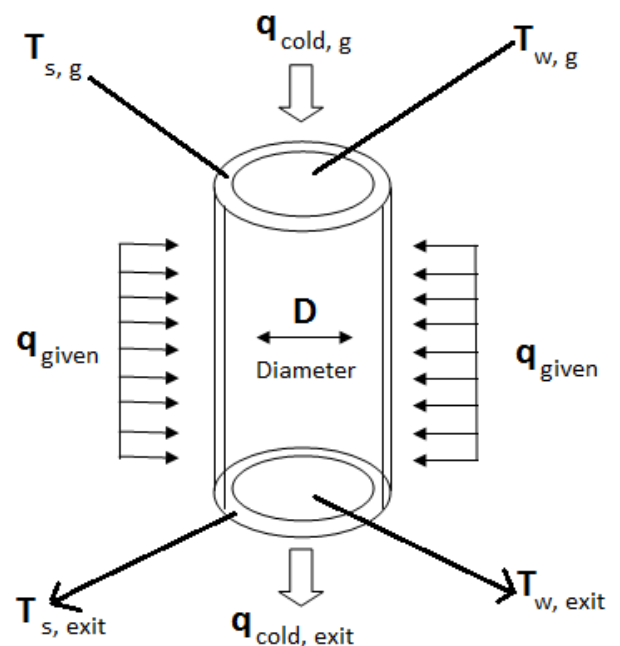


Fig. 2. Logic-based representation of the structure of the system

Using Newton's cooling law [41], the amount of energy delivered to a pipe over time has been determined:

$$q_{given} = h_w A_w (T_{s,avg} - T_{w,avg}) \quad (7)$$

$$= h_w (\pi D l) \left(\frac{T_{s,g} + T_{s,exit}}{2} - \frac{T_{w,g} + T_{w,exit}}{2} \right) \quad (8)$$

Whereas the surface area of the pipeline is represented by A_w , and l is the length; the cooling water temperatures at the entrance point it $T_{w,g}$ and $T_{w,exit}$ at the exit point. Due to the cooling water, per unit heat cooled at given a time was

$$q_{cold} = q_{cold,exit} - q_{cold,g} = Q_w p_w c_w (T_{w,exit} - T_{w,g}) \quad (9)$$

Whereas the inflow of water, per unit at a given time is Q_w ; p_w and c_w is weight of water and specific heat, respectively. The energy conservation principle states that equations 8 and 9 are equal; as a result, the unknown temperature $T_{w,exit}$ may be computed if three temperatures, $T_{s,g}$, $T_{s,exit}$, and $T_{w,g}$, are known

$$T_{w,exit} = \frac{(C_1 - C_2) T_{w,g} + C_2 (T_{s,g} + T_{s,exit})}{C_1 - C_2} \quad (10)$$

where

$$C_1 = Q_w p_w c_w, C_2 = h_w \pi D l / 2. \quad (11)$$

5. Neelum-Jhelum HPP

The Neelum Jhelum power plant was constructed on the Neelum River in Azad Kashmir, Pakistan, for the diversion of the water towards the Jhelum hydroelectric power plant.

5.1 Demography

This power plant is located about 41 km from Muzaffarabad and has a capacity of generating ~ 969MW. Due to some major cracks in the end tunnel on 6 July 2022, HPP was shut down and resumed its work in July 2023. The Neelum Jhelum is a 60m high and 125m wide gravity dam; it has a capacity of 8000000 m³, and 2800000 m³ of water can be used [42]. This dam diverts 280m³ towards the southeast into a 28.5 km-long tunnel (headrace). The water enters the surge bower at the tunnel's end, which has an 820m long surge tunnel and a 341m tall surge shaft to save water hammer. The water is separated from the surge chamber into four independent penstocks, each of which feeds one of the four. 242 MW Francis turbine generators are located underground; the water is set to go southeast into the Jhelum River through a 3500m long tail-race tunnel after being utilized to produce energy [43]. The height difference between the dam and the power plant allows for a water-pumping head of 420m on average. The end of the

tunnel cracked and jammed, which result shutdown of the dam in July 2022.

5.2 Thermal Properties of Material

The Thermal conductivity of Pipe was 40.0, Rock was 1.8, and placing concrete was 2.6 kcal/m h °C, respectively. The Density of Pipe was 7850 (steel), Rock was 2600, and the density of concrete was 2300 kg/m³, respectively. Likewise, the atmospheric convectivity of Placing concrete and Rock was 12 kcal/m² h °C, and the strength of 370 kg/m³ Cement content was 260 kg/cm² (25.5 MPa) at the age of one month. The thermal parameters of the coolant were as follows

- Inlet temperatures for the pipe cooling ranged from 22 to 30 °C.
- While cooling water flow varied from 0.8 to 1.5m³/h, the pipe diameter (ID) was around 24.2 mm.
- The coolant water's entry temperature was 26°C, and the measured volume was 1.08m³/h, approximately equal to a 0.234 m³/h velocity rate.

6. Modelling and Results

In this study, the transient temperature in the concrete foundation was obtained by solving the heat conduction equation with hydration heat using the FEM code. Pipe cooling was modelled by treating the internal pipe surface as a convective boundary, and the heat transfer coefficient was obtained from Reynolds-number correlations. Whereas specific conditions for the FEM code were set explicitly, accounting for hydrodynamic and thermal entrance lengths under varying flow conditions. Spatial and temporal convergence were checked via mesh refinement and iterative coupling tolerances between the pipe model and the concrete domain. Comparisons of peak values and temperature gradients were used to confirm the FEM implementation for thermal behavior. The temperature variance due to the heat of hydration was measured, whereas the spread footing was a reinforced concrete building set on a rock foundation.

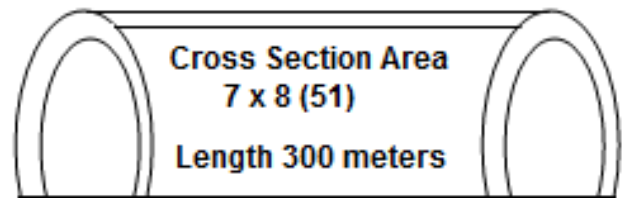


Fig 3. U-Shape Bypass tunnel of HPP

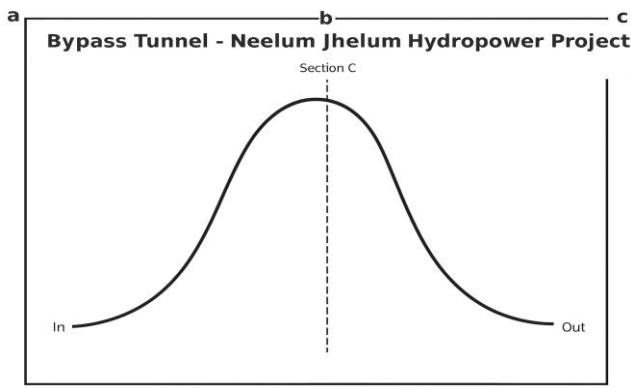


Fig 4. Pipe Looping Layout

The chosen Bypass tunnel of the Neelum Jhelum hydropower project is shown in Figure 3. Rock has a lower temperature gradient than concrete that has been laid. In comparison to the rock, the concrete was measured more precisely. To account for the impacts of internal flow, each line element was given a number along the cooling water's direction of flow. The overall number of nodes in this finite element mesh was 31,155, while the total number of solid and line elements was 30,800 and 800, respectively. It was thought that the distribution of rock temperature varied linearly with depth; at section C as shown in Figure 4. The actual temperatures were compared to the forecasted outcomes as shown in the following Table 1; measured and predicted values show very close agreement ($\approx$ within $\pm 0.6^\circ\text{C}$, RMSE = $0.2\text{--}0.6^\circ\text{C}$ and MAE = $0.1\text{--}0.4^\circ\text{C}$).

Table 1

Forecasted Outcomes of the Temperatures

Sr #	Point	Forecasted Temperature	Measured Temperature
1	Initial Concrete Temperature	30	30
2	Upper Rock Plane	33	32
3	Lower Rock Plane	27	28

Figure 5 displays the concrete's adiabatic temperature increase curve, which was produced using calorimeter equipment, and the reaction rate was 1.2, the highest temperature K was 45.0°C , and the delayed time was 0.023 days (≈ 33.1 min).

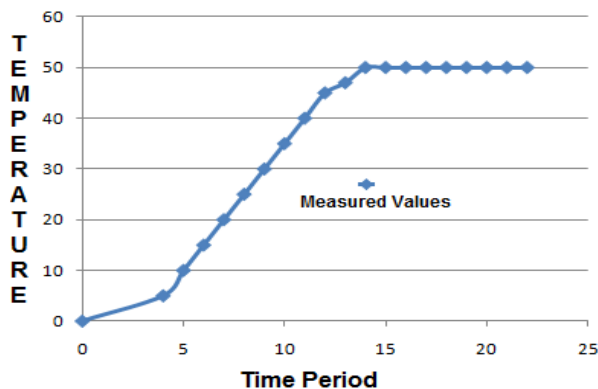


Fig 5. Adiabatic Temperature Increase Curve

The concrete temperature's variation at section C is a result of the hydration heat of cement; the data demonstrates that concrete cools more quickly when pipes are present. At point b, which is near the cooling pipe, due to their closeness to the cooling pipe, point b experiences a greater fall in concrete temperature than do points a and c. At locations a and c, respectively, the temperature of the concrete decreased due to convection in the environment and heat transfer from the rock. The temperature histories of the measured and numerical data show comparable patterns in the following Figure 6.

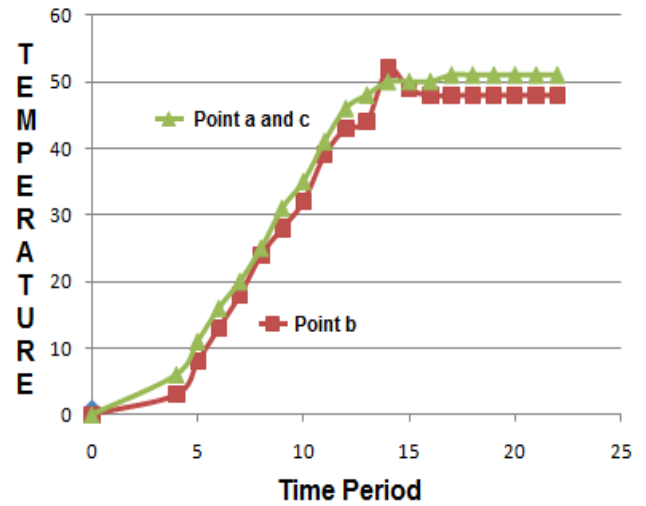


Fig 6. Graphical Representation of measured and calculated values at point a, b & c

Both the actual results and the predicted results show the same trends; this indicates the effectiveness of pipe cooling, whereas at point c, the highest temperature was 2°C higher than the expected temperature due to contact with rock. The analytical point was close to the rock surface, but the location of the temperature sensor was not shown discrepancy resulted from this distinction. To evaluate the reliability, a comparison was conducted between the model-predicted temperatures and field-recorded measurements. RMSE remained low, i.e., $0.2\text{--}0.6^\circ\text{C}$, which demonstrated that there are no notable deviations between predicted and measured temperatures. Whereas MAE remained within $0.1\text{--}0.4^\circ\text{C}$, so the average magnitude of error was minor. These results validate the robustness of the coefficients and strengthen the credibility assessment. The analysis assumed that the incoming cooling water temperature was 25°C . The findings demonstrate that the analytical technique can forecast changes in cooling water temperature. The outcome suggests that the cooling water temperature increase is accurately predicted. The findings demonstrate that the interior movement concept used in this work can successfully model the definite issue.

7. Sensitivity Analysis Using Neutrosophic for Robustness of Model

Classical and Fuzzy logic are extended with the neutrosophic approach to deal with imprecise values [44]. To handle uncertainty, the neutrosophic set used three degrees, including indeterminacy (i) along with truth (t) and falsehood (f). Different research has proven that the neutrosophic is best suited for the robustness of the Model in case of Sensitivity Analysis[1, 45]. By using equation (10) as explained in equation (11), we expand $T_{w, exit}$ with the neutrosophic approach, t_i , f_i , and i_i represent the truth, falsehood, and indeterminacy of each criterion.

$$T_{w, exit} = \sum_{i=1}^n w_i (t_i \oplus f_i \oplus i_i) \quad (12)$$

In the current study, the physical property ranges for water (22–30 °C), the flow rates, and pipe assumptions were considered. The sensitivity analysis conducted through a neutrosophic reveals a multi-dimensional assessment of the robustness of the modelled coefficients by explicitly incorporating neutrosophic three-degree into the evaluation of each physical parameter.

- Reynolds numbers demonstrated consistency in the measured coolant flow rate of 1.08 m³/h and pipe diameter of 24.2 mm by yielding a Reynolds number of 17,573.
- Neutrosophic analysis showed flow (t - 0.95), indeterminacy (i - 0.04) due to fluctuations in measured flow (0.8–1.5 m³/h), while falsehood (f - 0.01) reflects the near-impossibility of laminar flow for this configuration.
- The hydraulic and thermal entrance lengths were calculated to be 0.242 m (under the 10D rule) and exhibit strong robustness under neutrosophic evaluation. Truth-value associated with the stability lengths was high (t - 0.88), which validated the turbulent-flow theory.
- Indeterminacy (i - 0.10) due to unmodelled pipe-surface roughness effects, thermal stratification due to variations in tunnel ambient conditions.
- The robustness of temperature-equilibrium conditions shows truth degree (t - 0.87), whereas indeterminacy (i - 0.11) arises due to fluctuating inlet temperature range (22–30 °C).
- Sensitivity of coolant circulation measurements also shows a high truth degree (t - 0.90), as the minimum required

flow for turbulence (0.246 m³/h) is far below the operational range.

Neutrosophic sensitivity analysis confirms that the modeled coefficients are highly robust, with low falsehood scores and well-bounded indeterminacy, indicating reliable thermal-hydraulic performance of the tunnel cooling system.

8. Conclusions

Using a finite element modeling program with numerical analysis, the thermodynamic research of water consumption temperature in concrete frameworks with pipe preservation mechanisms was conducted. For the assessment of the measured and predicted outcomes, a finite element analysis program was created that accurately predicts the thermodynamic trend of concrete and was verified through Neutrosophic analysis. Neutrosophic analysis demonstrates that the modeled coefficients exhibit strong robustness, characterized by minimal falsity levels and tightly constrained indeterminacy, confirming the dependable thermal and hydraulic behavior of the tunnel's cooling system.

Based on the current study, it is recommended that the continuous thermal monitoring should be strengthened by installing high-resolution temperature and pressure sensors. Post-construction thermal diagnostics, like thermal imaging, should be installed for real-time monitoring. Cooling water flow rate from 0.8 to 1.5 m³/h should be optimized through automated control systems. Neutrosophic-based assessment may be implemented in civil structural health monitoring.

Despite providing the robustness of thermal and hydraulic parameters, the current study has some limitations. Due to the assumption, i.e., adiabatic and standard values, reduces its precision is reduced. The model used the tunnel cooling pipes, with constant material properties; these parameters may vary with pipe aging and environmental temperature gradients. The analysis does not incorporate sensor data, limiting its ability to detect nonlinear or sudden variations in temperature fields. Moreover, heat generation due to hydration was represented by an adiabatic temperature rise curve, but creep and shrinkage were not included in a fully coupled FEM code. Therefore, a more detailed stress and cracking analysis is required in future work.

9. Declarations

Competing Interests: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Ethics Approval and Consent to Participate: Not applicable to this study

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Data Availability Statement: The Forecasted and Measured data used to complete this study are given in Table 1 of the manuscript.

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