Computers and Concrete, *Vol. 24, No. 5* (*2019*) *437-444*
DOI: https://doi.org/10.12989/cac.2019.24.5.437

An automated control system for concrete temperature development in construction

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(*Received March 26, 2019, Revised September 19, 2019, Accepted October 8, 2019*)

Abstract. PLC and its expansion module, electric ball valve and cooling pipe, electric heating steel plate and various components of the system, which is used to control test and process data. By automatically adjusting the opening of the valve, the system makes the top temperature and cooling speed develop along the ideal temperature diachronic curve. Moreover, the system enables the temperature difference between inside and surface of test block limited in a given range by automatically controlling the surface board heating. The method of physical simulation test by sandbox with built-in cooling water pipe and heating rod is adopted. On the premise of a given standard value, the operation of the system is checked under different working conditions. Further, an extension of this system is proposed, which enables its application to obtain some thermal parameters when cooperating with numerical simulation.

Keywords: Programmable Logic Controller (PLC); automation; temperature control; concrete construction; concrete

1. Introduction

High concrete temperatures increase the rate of hydration, thermal stress, the tendency for drying shrinkage cracking and permeability, and decrease long-term concrete strengths and durability due to cracking (Anton and McCullough 2002, David *et al.* 2010, Schutter 1995). Improper concrete temperature is also an important influence factor on maturity development and early-age performance (Seyed-Hassan *et al.* 2007); Nader and Hamidou 2010). As for mass concrete, thermal stress is a major factor to induce crack (Dolmatov 1971, Dolmatov and Neidlin 1968). Therefore, the temperature control in early age for the concrete structure is always important. The main temperature control indicators commonly used in engineering are maximum temperature, cooling rate, temperature difference between inside and outside, etc. (Zhu 1999). And the main methods to realize the indicators are casting temperature control, pipe cooling and surface insulation (Qiang *et al.* 2012). In this paper, the latter two methods will be discussed.

Figs. 1-2 show the typical layout of pipe and surface insulation in sluice and dam. Although the maximum temperature is mostly influenced by pipe cooling, and the temperature difference between inside and surface is mostly influenced by surface insulation, actually both of two temperature control methods influence the three indexes. Engineering practices indicate that surface heat preservation can reduce the temperature difference between the surface

(a) Layout of pipe in sluice deck

(b) Layout of pipe in the dam

Fig. 1 Layout of cooling pipe in a mass concrete structure in construction

and internal concrete of a pier as well as the surface tensile stress at the early age but can elevate the temperature increase and the amplitude of the temperature drop, resulting in markedly increased internal tensile stress in the later stage (Huang 2018).

Before the concrete casting, the temperature control

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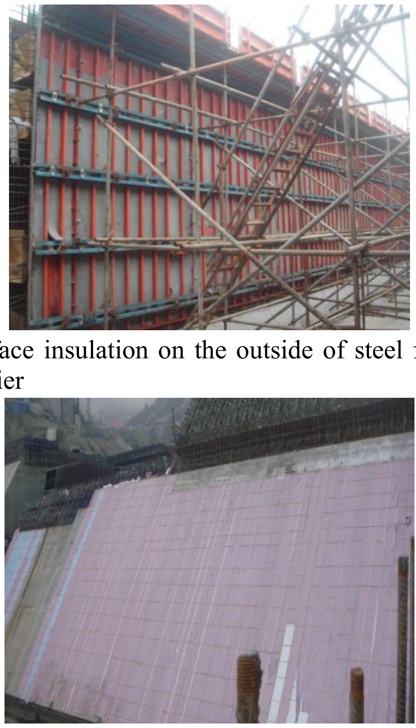
http://www.techno-press.org/?journal=cac&subpage=8
ISSN: 1598-8198 (Print), 1598-818X (Online)



(a) Surface insulation on the outside of steel form for sluice pier

(b) Surface insulation on the downstream face of a dam

Fig. 2 Surface insulation on the mass concrete structure in construction

indexes and the corresponding temperature scheme are usually suggested by numerical simulation results of concrete structure construction (Chen *et al.* 2003, Malkawi *et al.* 2003, Guo *et al.* 2011). In the pipe cooling scheme, it includes pipe layout, water temperature, beginning time, ending time, water flux during different periods. In the surface insulation scheme, it includes covering material type, thickness, the beginning time and ending time. As for a certain structure, a high precision numerical simulation can provide the best-optimized temperature development curves which will induce the least tensile stress to farthest avoid crack (Zhu *et al.* 2013). Actually, for the concrete in different areas, different mixtures, different casting temperatures and different environments, the optimized ideal temperature curve is obviously different (Xie *et al.* 2012). The diversity of the site situation and the complexity of the temperature control scheme sometimes make the scheme less practicable. Besides, some unforeseen circumstances will make it worse, such as a sudden cold wave or unsteady temperature of inlet cooling water.

According to the practical experience of many projects, the temperature scheme is difficult to implement well, and sometimes the actual temperature changes obviously with the temperature control index. Consequently, cracks appear inevitably during construction. Additionally, as the temperature control effect is the most concerning factor during the construction process, monitoring data should be utilized fully to predict risk zones and guide engineers to take measures as early as possible to prevent cracks. Few studies, however, have been concerned with these factors when designing a temperature control scheme for a concrete dam (Zhou *et al.* 2018). In current engineering, temperature control index mostly relies on manual control, which inevitably results in errors of reading, low control frequency and other faults due to the influence of human factors. In order to make the factual temperature well controlled as the indexes, an automated system was developed in this paper to accurately control the whole course of pipe cooling and surface insulation.

The current literature shows that the similar temperature automated control systems have been applied in some areas, such as chemical engineering (Park *et al.* 2011), civil engineering (Katte *et al.* 2011, Zhang *et al.* 2009), medicine curing (Cha *et al.* 1988), material processing (Tanaka *et al.* 2013), etc. But the control demands and courses of such systems are relatively simple. Most of them just require constant temperature. In concrete construction or concrete test, the control process is more complex and there are many indexes, (Poursaee and Weiss 2010, Bamforth 2007, Reclamation 1988). For example, the maximum temperature, the rate of temperature drop and the temperature difference between inside and outside. Programmable Logic Controller (PLC) is a device which can provide precise control to a complex course flexibly (Yilmaz 2010, Maraba and Kuzucuoglu 2011, Ahiska 2012, Bayindir and Cetinceviz 2011). Based on PLC, this paper developed an automated control system for the concrete temperature to ensure the temperature control schemes and indexes could be executed perfectly in construction.

In the current research, concrete temperature control automatic system has been developed to a certain extent. Peng (2019) developed a wireless temperature measurement and control system for mass concrete based on ZigBee technology. It lays a good foundation for wireless control of concrete temperature control system. Li *et al.* (2016) experimented with an intelligent control system for cooling water. Intelligent temperature control technology proposed by Zhang et al. (2018) has been applied in many projects.Lin *et al*. (2014) has proposed a real-time temperature data transmission approach for intelligent cooling control of mass concrete. However, there is no a concrete temperature control system that simultaneously controls cooling water flow and surface heating.

2. Material and methods

2.1 Objects

The automated system in this paper controlled the inside and surface temperature effectively by adjusting the cooling water flux and surface insulation board temperature. The expected objective is to realize the automated adjusting of the temperature duration curve, including the concrete top temperature, temperature decreasing velocity and the difference between inside and surface. When the system is applied in temperature control, the temperature of concrete inside and surface will develop as the ideal temperature duration curves which may be obtained by numerical simulation in advance. And the difference between the factual temperature duration curves and the ideal ones can be controlled in a limited magnitude. After the successful laboratory tests, it is proved that the system has certain

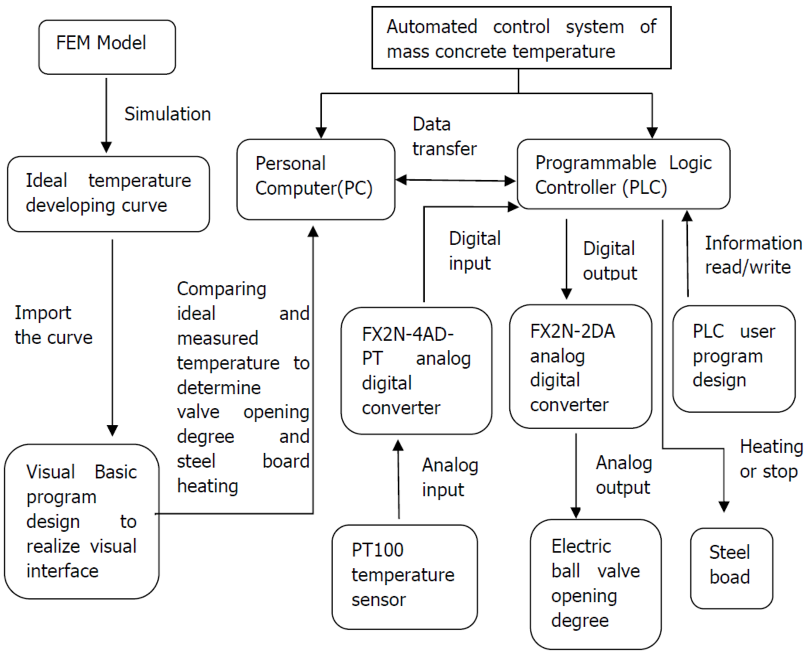


Fig. 3 The system components and operation procedure

advantages in temperature control and crack prevention of concrete structure construction.

2.2 Component of the system

The major development tools of this system are PLC and Visual Basic (VB). The PLC type is FX2N-16MR from Mitsubishi Company, and the corresponding compile software is GX Developer Version 7. The cooling water flux was adjusted by an electric ball valve. The surface insulation control was realized by electricity heated steel board. The temperature of the test block was obtained by PT100 industry temperature sensor. The main control program in the personal computer (PC) coded in VB operated the data transmission, calculation, reading and writing.

2.3 Working principle of the system

The whole system function procedure is shown in Fig. 3. From the figure, the ideal temperature duration curve was imported in the VB program at first. Then the system began running. The PT100 sensor measured the temperature at a set time interval, such as every 5 minutes or 0.005 day. Every time the temperature module of PLC obtained a temperature value, the VB program would compare the value with the temperature on the ideal temperature duration curve at the corresponding age. By calculation, a valve opening degree could be got and reported back to PLC. The opening degree would be transferred to the electric ball valve after the digital signal converted to analog signal by PLC. Consequently, the flux of cooling water could be automatically adjusted.

As for the surface insulation board, the procedure is similar to the above. The difference is that the imported control index is only one value, not a curve. The value is the

Table 1 The relationship of temperature deviation and water flux

Measured value minus ideal value (°C)	>2.0	[1.5, 2.0]	[1.0, 1.5]	[-1.0, 1.0]	<-1.0
Flux (m^3/d)	80.0	60.0	40.0	20.0	0.0

optimized temperature difference between the interior and the surface. At set time, the temperature difference would be compared between the measured value and the index by program. The results would be transferred to an executor to decide whether the surface steel would be heated or not.

In the tests of this paper, the water flux control algorithm is set as follows. When the value of the measured temperature subtracted from the ideal temperature at a certain age is more than 2.0°C, the ball valve will open fully with the corresponding flux of 80 m^3/d. When the value is between 1.5°C to 2.0°C, the flux should be reduced to 60 m^3/d. The detailed relationship of the temperature deviation and water flux can be seen in Table 1. The relationship is not completely fixed in the VB program. It can be modified with different engineering situations.

The surface insulation control principle is presented as follows. We assume that the ideal temperature difference index between the inside and the surface is X, which means the maximum temperature difference should be less than X. When the measured inside temperature is X+1.0 higher than the surface temperature, the heating power starts working. When the measured inside temperature is X-1.0 lower than the surface temperature, the heating power stops working. By this way, the factual temperature difference can be controlled in [X-1.0, X+1.0].

2.4 Test procedure

A box with the dimension of 1.7 m×1.20 m×0.83 m was

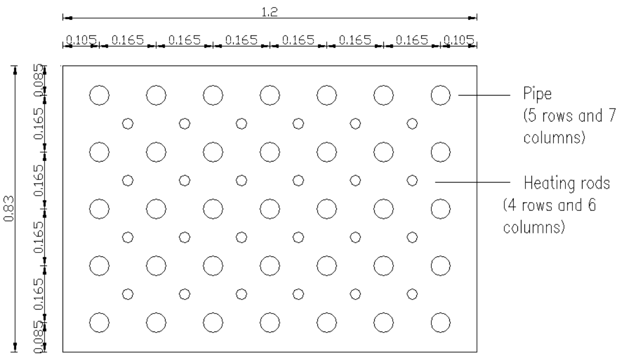


Fig. 4 Heating rods and pipe layout on test block section (m)

Fig. 5 Parts of heating rods and pipe

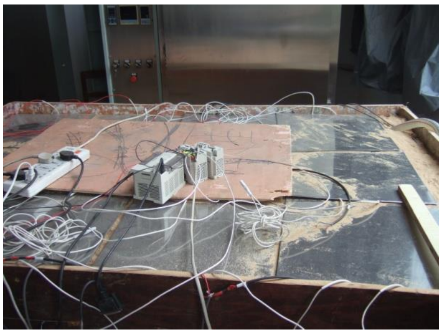


Fig. 6 Heating steel board and PLC on top surface

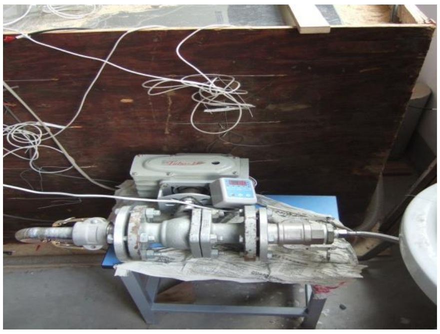


Fig. 7 Electric ball valve

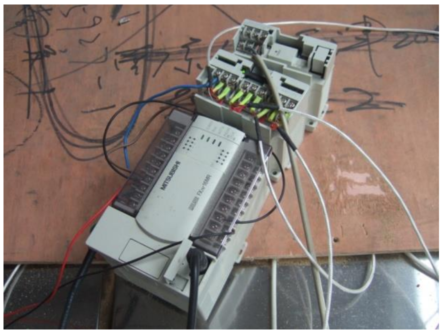


Fig. 8 PLC and extended modules

Fig. 9 System testing

created in a laboratory. The surround faces of the box were wood mould. There were 24 heating rods and a 60m long plastic pipe fixed in the box. The rods, pipe layout, box section and size can be seen in Fig. 4. Parts of the rods and pipe can be seen in Fig. 5. The rods were arranged separately in 4 layers. The pipe, with only one inlet and one outlet, was fixed with U shape turns in 5 layers. The diameters of pipe and rod are 0.028 m and 0.015 m separately.

It must be pointed out that fresh concrete is replaced by sand in the tests. There are 3 reasons for the replacement. First, the thermal parameters of sand are closer to concrete than those of other substitutes. Second, the sand heated by rods can simulate the hydration process of concrete for many times, while the real concrete can only be hydrated once. That means the test can be repeated for many times. Third, it is very difficult to deal with such a large scale concrete block in the laboratory when the tests are completed.

After the box was full of sand, the top surface was covered with 8 steel boards which could be heated by electricity. The sensors in the steel board could provide its temperature, that is, the surface temperature of the specimen. The next step was to connect all the components with data lines or electric cable, referring to Fig. 3. The main temperature control components, including steel board, electric ball valve and PLC are shown in Figs. 6-8. A PT100 sensor was fixed near the center of the test block to measure the inside temperature.

3. Results

As is shown in Fig. 9, the system was tested by some cases. This paper presents three typical cases. In these cases, test time was shortened by less than 0.5 day to fast simulate the temperature rise and fall of concrete. In the factual engineering, the temperature control will last over several days, or even months.

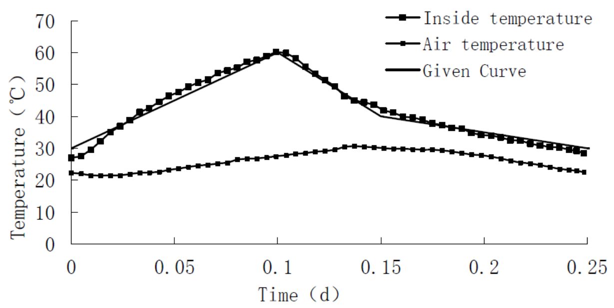


Fig. 10 Comparison between measured inside temperature and given curve in test case 1

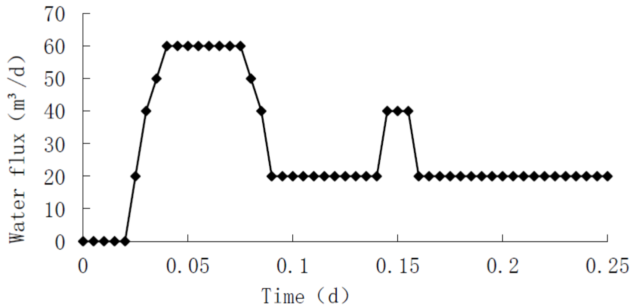


Fig. 11 Cooling water flux duration curve in case 1

Test case 1: Only water flux automatic adjustment function was tested in this case. The given ideal inside temperature duration curve developed along the following points: (0, 30), (0.1, 60), (0.15, 40), (0.25, 30). The first number in every bracket is time /day, and the second number is temperature /°C. The given curve is formed by connecting these points by lines. The test results are shown in Fig. 10 and Fig. 11.

Test case 2: Only surface temperature automatic adjustment function was tested in this case. The given temperature difference index between the inside and surface was 6.0°C. The test result is shown in Fig. 12.

Test case 3: Both water flux and surface heating automatically adjustment functions were tested in this case. The given ideal inside temperature duration curve developed along the following points: (0, 30), (0.075, 60), (0.15, 40), (0.3, 20). The first number in every bracket is time /day, and the second number is temperature /°C. The test results are shown in Fig. 13 and Fig. 14.

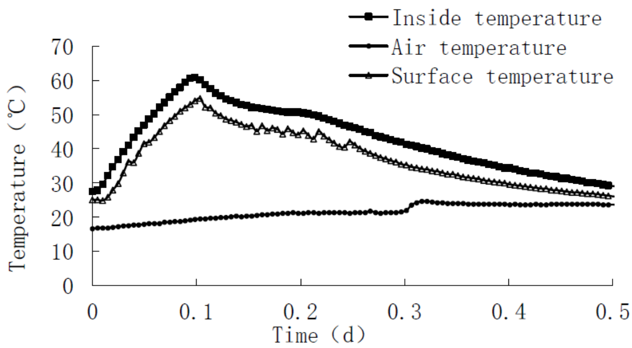


Fig. 12 Comparison between measured inside temperature and surface temperature in test case 2

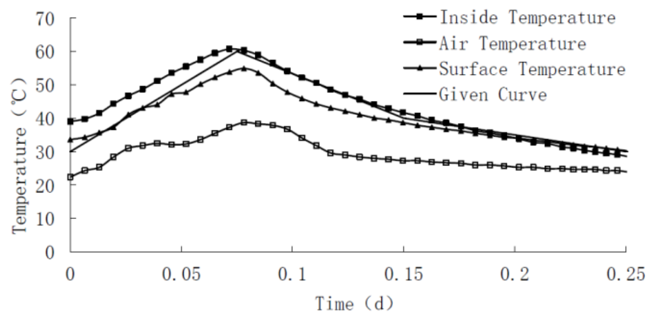


Fig. 13 Comparison of measured inside temperature, surface temperature and given duration curve in test case 3

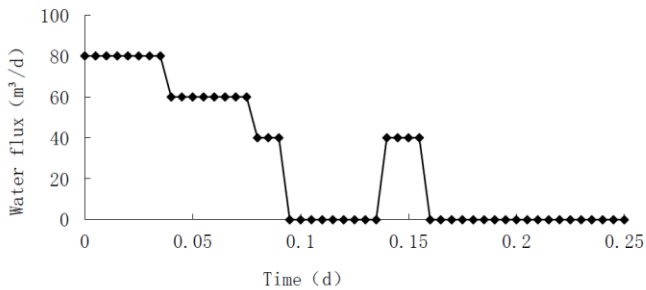


Fig. 14 Cooling water flux duration in test case 3

4. Discussion

4.1 Comparison between test results and given indexes

In test case 1, the initial ideal temperature was higher than the measured value in the first 0.02d, as shown in Fig. 10. Therefore, the water flux in the first 0.02d was zero, as shown in Fig. 11. After that, the inside temperature began rising over the ideal curve. Then the valve opening degree became larger and larger until the temperature difference between the measured value and the given value was less than the setting data in Table 1. In Fig. 11, the flux fluctuated according to the relation of measured temperature and given value. Near the time of 0.15d, the measured temperature became higher than the ideal curve again in Fig. 10, so the water flux became larger consequently in Fig. 11.

In test case 2, the inside temperature was heated to 60°C in 0.1d by rods. And then rods power was shut off. Therefore, the temperature began decreasing naturally. Because water cooling was not running, the temperature decreasing velocity was slower than that of case 1. In Fig. 12, it can be seen that the measured surface temperature curve went along with the measured inside temperature curve. In the whole course, the difference between the two curves could be controlled in the range of [5.0, 7.0]°C. The surface temperature fluctuated near the time of 0.2d, which showed the heating power of the surface board automatically on and off frequently.

In test case 3, the initial measured temperature was higher than that of case 1 and case 2. Before the temperature peak, the measured temperature was always

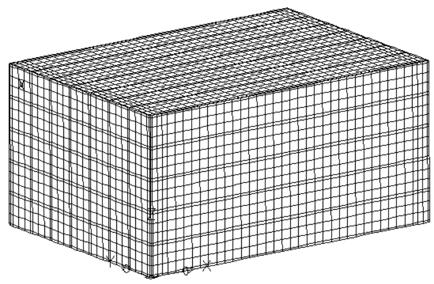


Fig. 15 Finite element model of the test block

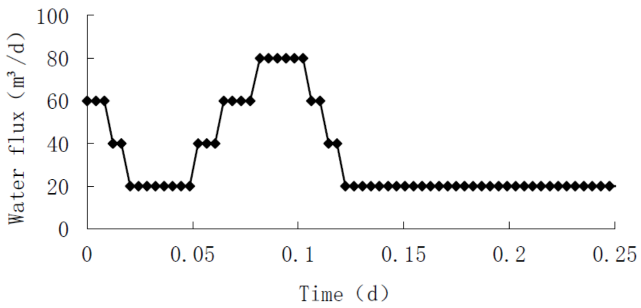


Fig. 16 Cooling water flux duration curve in physical simulation

higher than the ideal curve, as shown in Fig. 13. Therefore, the water flux kept maximum, as shown in Fig. 14. When the measured inside temperature was near ideal curve between 0.1d to 0.15d, the water flux became zero. During the whole course, whatever changing the inside temperature and air temperature taken place, the surface temperature could be kept lower than the measured inside temperature within a range of [5.0, 7.0]°C.

From the results of the above 3 test cases, it can be drawn that the system can control the top temperature automatically, the temperature decreasing velocity, and the temperature difference between the inside and surface. And the control precision is satisfying.

4.2 Comparison between physical test and numerical test

The ideal temperature curve in the above test cases came from arbitrary given points instead of a numerical simulation. Although the test results had proved that the system could control temperature effectively, the corresponding relation between physical simulation and numerical simulation was further tested as well.

A finite element model, shown in Fig. 15, was created to simulate the cooling course and compare with the lab test results. The heat conductivity coefficient and thermal diffusivity of sand were 10.83kJ/(m·h·°C) and 0.00583(m2/h). In the FEM simulation, the top surface of the test block was naked. The surface heat exchange coefficient of the surrounding wood mould was 25.0 kJ/(m2·h·°C); the top surface was 62.5 kJ/(m2·h·°C); the bottom surface was 8.3 kJ/(m2·h·°C). The cooling pipe was simulated by explicit model (Xie *et al*. 2011; Zhu *et al*. 2004). The heat exchange coefficient of the pipe wall is 375.2 kJ/(m2·h·°C) (Qiang *et al*. 2010).

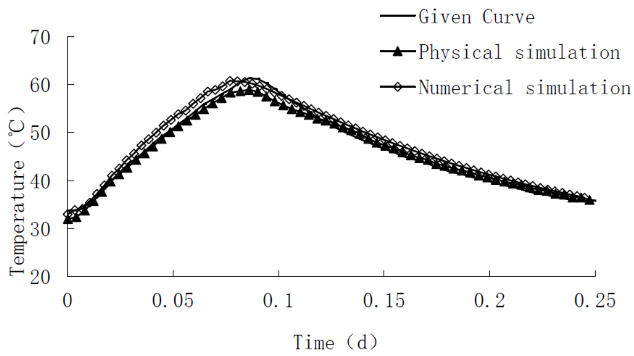


Fig. 17 Inside temperature comparison of physical simulation, numerical simulation and given curve

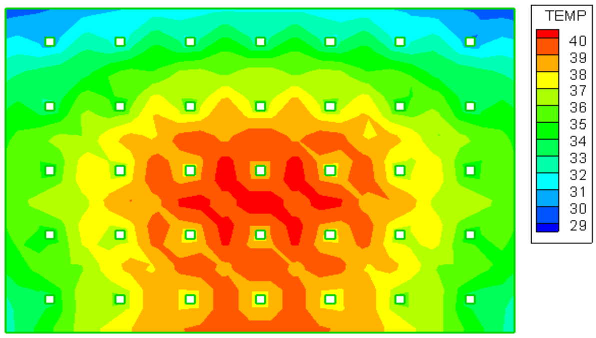


Fig. 18 Temperature cloud contour of numerical simulation at the center section of the test block when time is 0.2205d

The numerical simulation step length is 0.0035d. The water flux in Fig. 16 was measured in the lab test, which would be used in the numerical simulation. The comparison of the curves given, the laboratory test curves and the numerical simulation curves in Fig. 17 shows that they meet the requirements. It indicates that the system and FEM can be verified each other. Fig. 18 shows the temperature cloud contour of the center section at 0.2205d. It describes the temperature distribution on the section.

5. Conclusions

A system, including hardware and software, was developed to automatically control the whole course of temperature duration in the test block. The physical simulation tests in the laboratory show that the maximum error between measured inside temperature and given temperature curve can be limited in 2.0℃ by automatically adjusting the opening degree of the electric ball valve. It indicates that the top temperature and temperature decreasing velocity can be controlled automatically. Besides, the maximum error between the given index and the measured temperature difference of the inside and surface can be limited in ±1.0℃ by the steel board heating automatically.

Under the same conditions, the numerical simulation will achieve the same results with the physical simulation. It implies that the system can also be used to obtain some unknown thermal parameters of new type cooling pipe or surface insulation material by numerical inversion method.

The detailed temperature control indexes can be modified freely in this system for different projects. The system can be applied in concrete temperature control in construction and material test in the laboratory.

For further development, the control system can be simplified and a control system which is more suitable for construction site can be developed. In order to exclude environmental factors such as temperature influence and highlight the role of control system, a natural temperature development process condition can be added to the test verification.

Acknowledgements

This work is supported by the National Natural Science Foundation of China (51679074).

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