Estimation of economic efficiency of convective heating methods

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Abstract. The methods of convective heating of thin-walled monolithic structures constructed in winter conditions in tunnel formwork are considered. The classification of convection heating methods, based on the principle of heat flow to the heated structure, is made: traditional chamber heating, chamber heating with air ducts, convection heating with pre-form curtains, developed at the Department of Construction and the theory of structures of the South Ural State University. The efficiency of capital investments for the methods under consideration is determined on the basis of the determination of the area under the investment curve. The unit costs in rubles per cubic meter of heated concrete for the considered methods are calculated. The results on capital investments and specific costs for heat treatment of concrete by convective methods are compared. The authors draw the conclusions about the effectiveness of using the method of convection heating with pre-form curtains for heat treatment of monolithic thin-walled structures, constructed in tunnel formwork due to a more efficient use of energy from heat generators, which allows shortening the duration of concrete keeping.

1. Introduction
Since the beginning of the 2000s, there has been a growth trend in the use of monolithic concrete in civil engineering. At the same time, up to 40% of the total work in construction is carried out in winter conditions. A significant part, up to 65%, of monolithic reinforced concrete structures of residential and public buildings are thin-walled (slabs, walls with a surface module $M_p > 10$, where the surface modulus is the ratio of the surface of the cooled structure to its volume).

However, most of the existing methods of heat treatment of concrete were developed mainly for massive structures of industrial buildings, so the question of choosing the method and determining the parameters for heating the walls and ceilings of civil buildings becomes urgent.

One of the most common methods used for heat treatment of concrete thin-walled structures is the convection heating method, in which heated air is supplied to a room bounded by monolithic walls and ceilings. The transfer of heat from the heat generator to the surface of the formwork is carried out by convection. Further, due to the thermal conductivity of the concrete, the internal layers of the constructed structure are heated. External shuttering boards are insulated with effective heat-insulating materials, or thermoactive mats are used. Heat generators for convection heating are often electric heaters, because they are easy to install, high efficiency, low cost, the ability to quickly replace in the event of failure and a high degree of safety of maintenance personnel.
The analysis of winter concreting methods shows that for heat treatment of monolithic thin-walled structures, it is expedient to use convective heating methods [1-6]. This is due to low labor intensity, material intensity, energy intensity of these methods, as well as the possibility of combining with other methods of winter concreting.

Convective heating methods can be classified according to the principle of heat flow to the heated structure [7-9]. Proceeding from this, it is possible to single out the following methods: traditional chamber heating, chamber heating with air ducts, convection heating with pre-form curtains.

2. Traditional chamber heating
With the traditional chamber heating, the heat flow from the heat generator is fed into the closed volume of the tunnel and further, due to convective heat transfer [10-12], the inner formwork shields are heated Figure 1.

The advantages of the traditional chamber warming method include the minimum labor costs for the installation of heat generators and the fixing of the heat-insulating curtain that blocks the entrance to the tunnel.

The drawbacks of the method include the uneven temperature distribution along the tunnel height and, as a consequence, the risks of obtaining low strength values in the lower part of the walls in the area of contact with previously laid concrete of the previous floor.

3. Chamber heating with ducts
The essence of the method lies in the fact that the heat flow from the heat generator enters the distributor and further into the ducts that supply heat flow along the perimeter of the constructed walls Figure 2.

Air ducts are made of rubberized fabric. In length, they must have holes provided for the creation of jets of hot air, directed to the internal formwork boards.

Advantage of the chamber heating method with air ducts is the reduction of the risk of obtaining low strength values in the lower sections of the heated wall structures in comparison with the traditional chamber heating.

The shortcomings of the method include additional costs for the use of air ducts, as well as a slight reduction in the time required to withstand concrete with respect to the traditional chamber heating method.
4. Convective heating with pre-form curtains

Convective heating with pre-form curtains was developed at the Department of Construction Building and the Theory of Structures of the South Ural State University, patent for invention No. 2246466, registered in the State Inventory of the Russian Federation on February 20, 2005. The method is based on the transfer of heat flow from the heat generator to the area, limited by a heat-isolating curtain and formwork panels Figure 3.

The advantage of this method is to reduce the amount of heated space bordering the formwork, and to increase the efficiency of heat transfer to concrete.

The use of this method makes it possible to obtain a more even distribution of temperature and strength in heated walls and ceilings in comparison with the methods of traditional chamber heating and chamber warming with air ducts, and also by increasing the efficiency of using thermal energy to shorten the time required for concrete to reach the required values.

The drawbacks of the method include additional costs for the acquisition and installation of pre-form curtains for the organization of heat treatment of concrete. Pre-form curtains are made of two layers of tarpaulin with a heat-insulating interlayer of batting. It is also possible to use other materials.

The choice of concrete method for convective warming up of concrete should be made on the basis of technical and economic calculations for local construction conditions, taking into account the required strength of concrete. For floors with spans of up to 6 meters, erected in a tunnel formwork, the required strength of concrete at the time of shuttering, and in winter conditions, respectively, by...
the end of heat treatment, should be at least 70%, the strength of concrete monolithic wall structures at the time of freezing should not be less than 40% of the design strength [13].

5. Comparison of effectiveness of capital investments in various ways of conducting work

The carried researches testify that application of a method of convection heating with pre-form curtains allows to reduce the period of keeping monolithic structures up to 30%, to provide the required level of quality of erected structures [14-15]. However, in contrast to the traditional chamber heating, this method requires additional costs for the manufacture of an air flow distributor and heat-insulating pre-form curtains. Therefore, in order to economically evaluate the methods of convective heating, a comparison of the efficiency of investments with different methods of conducting work was performed, according to [16-19]. The data on the calculation of capital investments are summarized in table 1.

| Table 1. Calculating the efficiency of investments. |
|---------------------------------------------------|
| **Cost element**                                      | Distribution of costs by months of work, thousand rubles. |
|                                                    | 1  | 2  | 3  | 4  | 5  | 6  |
| Chamber                                            |    |    |    |    |    |    |
| Cost of materials                                  | 75,0 | 75,0 | 75,0 | 75,0 | 75,0 | 75,0 |
| Wages of basic workers                             | 30,0 | 60,0 | 90,0 | 120,0 | 150,0 | 180,0 |
| Cost of operation of heat generators               | 77,5 | 155,0 | 232,5 | 310,0 | 387,5 | 465,0 |
| Electricity costs                                  | 1226,3 | 2452,5 | 3678,8 | 4905,0 | 6131,3 | 7357,5 |
| Total direct costs                                 | 1408,8 | 2742,5 | 4076,3 | 5410,0 | 6743,8 | 8077,5 |
| Overheads 14,2%                                    | 200,0 | 389,4 | 578,8 | 768,2 | 957,6 | 1147,0 |
| Cost in current prices                             | 1608,8 | 3131,9 | 4655,1 | 6178,2 | 7701,4 | 9224,5 |
| Air ducts                                          |    |    |    |    |    |    |
| Cost of materials                                  | 157,5 | 158,3 | 159,1 | 159,9 | 160,7 | 161,5 |
| Wages of basic workers                             | 60,0 | 120,0 | 180,0 | 240,0 | 300,0 | 360,0 |
| Cost of operation of heat generators               | 77,5 | 155,0 | 232,5 | 310,0 | 387,5 | 465,0 |
| Electricity costs                                  | 1164,9 | 2329,9 | 3494,8 | 4659,8 | 5824,7 | 6989,6 |
| Total direct costs                                 | 1459,9 | 2763,2 | 4066,4 | 5369,7 | 6672,9 | 7976,1 |
| Overheads 14,2%                                    | 207,3 | 392,4 | 577,4 | 762,5 | 947,6 | 1132,6 |
| Cost in current prices                             | 1667,2 | 3155,5 | 4643,8 | 6132,1 | 7620,4 | 9108,7 |
| Pre-form curtains                                  |    |    |    |    |    |    |
| Cost of materials                                  | 437,5 | 527,5 | 617,5 | 707,5 | 797,5 | 887,5 |
| Wages of basic workers                             | 120,0 | 240,0 | 360,0 | 480,0 | 600,0 | 720,0 |
| Cost of operation of heat generators               | 77,5 | 155,0 | 232,5 | 310,0 | 387,5 | 465,0 |
| Electricity costs                                  | 858,4 | 1716,8 | 2575,1 | 3433,5 | 4291,9 | 5150,3 |
| Total direct costs                                 | 1493,4 | 2639,3 | 3785,1 | 4931,0 | 6076,9 | 7222,8 |
| Overheads 14,2%                                    | 212,1 | 374,8 | 537,5 | 700,2 | 862,9 | 1025,6 |
| Cost in current prices                             | 1705,4 | 3014,0 | 4322,6 | 5631,2 | 6939,8 | 8248,4 |

The estimated period of work on heat treatment was adopted for 6 months, which corresponds to the period of winter concreting in the climatic conditions of the Southern Urals and Western Siberia, with an average monthly temperature of minus 11 °C [20]. The calculation was carried out on 1000 m3 of concrete heated during the calendar month.

Data for the calculation are obtained from the financial and economic departments of construction companies in the city of Chelyabinsk.

On the basis of Table 1 investment schedules were plotted according to the months of work for various convective heating methods Figure4.
6. Conclusion

The analysis of these graphs allows to make the following conclusions:

1. The minimum investment for 6 months of winter concreting during the heat treatment of 1000 m$^3$ of concrete monthly has a method of convection heating with pre-form curtains - 8248.4 thousand rubles, in addition, the area under the investment curve of this method is the smallest, therefore, the investment efficiency is the highest;

2. The largest investment for 6 months of winter concreting requires a method of traditional chamber heating - 9224.5 thousand rubles and the efficiency of investment of this method is the lowest, since it has the largest area under the investment curve;

3. Methods of chamber heating with air ducts and convection heating with pre-form curtains in the first months of production require large investments related to the acquisition of additional equipment, but in the following months, due to lower energy consumption, increased formwork turnover and heating equipment, financial savings occur.

Thus, the use of the convection heating method with pre-form curtains for heat treatment of monolithic structures in comparison with traditional chamber heating allows reducing the cost of winter concreting up to 10%, reducing the energy consumption by up to 30%.

4. The cost per unit of heated concrete is: 1537.4 rubles/m$^3$ with traditional chamber heating, 1518.1 rub/m$^3$ with chamber heating with air ducts, 1374.7 rub/m$^3$ with convection heating with pre-form curtains, which indicates about the lowest unit costs per unit of heat-treated concrete of thin-walled structures by the method of convection heating with pre-form curtains, in spite of higher capital investments in materials at the initial stage.

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