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Transient Thermal Analysis of the Hollow Gravity Dam of the ITAIPÚ Hydroelectric Power Plant

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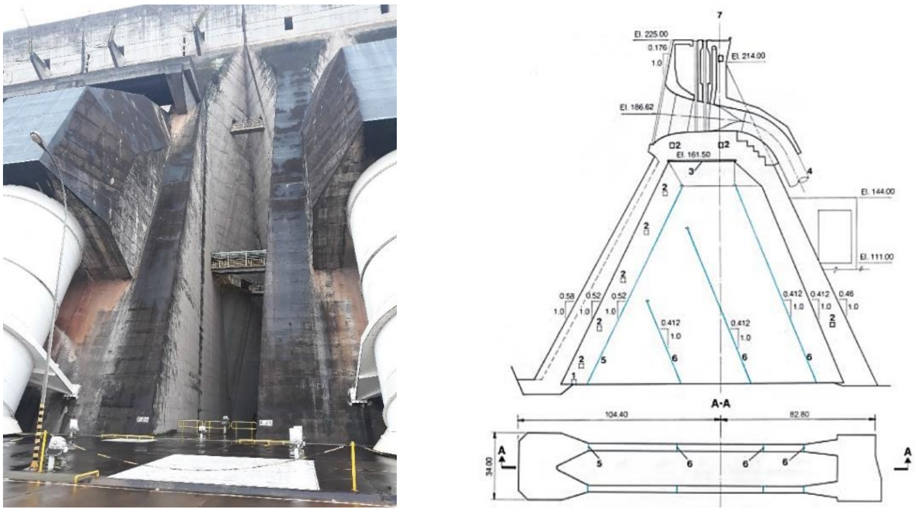
Abstract. Large critical structures, such as dams perform a lot of functions as water supply and power generation. Since this kind of structures must be constantly studied to guarantee safety behavior during their useful life and after that. Thus, Numerical computational tools are used in this type of structure to reevaluate limit values of several parameters related to thermal and structural performance. Therefore, in this work, was used the computer simulation program Ansys, based on the Finite Element Method (FEA) to perform a thermical analysis of the F-5/6 block of hollow gravity dam from the Itaipu Hydroelectric Power Plant. In order to know the temperature distribution resulting from the thermal variation. A thermal-transient analysis was performed during the first four years when the reservoir was filled in 1982. To perform this analysis, the data from the external thermometers were interpolated and used as initial conditions. Subsequently, at the location of the internal thermometers, test points were implemented in the model in order to compare the temperatures obtained in the numerical simulation with the data recorded by the thermometers. The results was satisfactory.

Keywords: Thermal-transient, FEM, Ansys, Itaipu.

1 Introduction

The dams can be classified into two major groups according to their construction material: (i) concrete dams, considered rigid, and (ii) conventional earth or rockfill dams (non-rigid dams). Concrete dams can be classified according to their geometry in gravity dams; buttresses; arch and hollow gravity dam.

Hollow gravity dams are structures characterized by an empty space at their core, seeking to optimize the amount of concrete used in their construction. In this type of dam, the weight of the water on the sloping upstream face prevents it from tipping over and its smaller area base reduces uplift pressure [1]. **Figure 1** shows the Itaipu hollow gravity dam.



(a) **(b)**

Figure 1. Itaipu hollow gravity dam (a). Cross section of the main dam [2] (b).

For the execution of this kind of structures, a high amount of concrete is necessary, which can cause great volumetric variations due to the generation of heat from the cement hydration reactions. Because the low thermal conductivity of the concrete, the heat from these types of reactions is slowly dissipated. In the early ages of concrete, the highest temperatures are located inside the dams and the lowest on the surface. This generates a temperature gradient [3].

In addition to thermal variations, there are several other external loads can cause deformations and stresses in a dam, such as: own weight, hydrostatic pressure, uplift pressure, among others. Due to the number of variables involved in thermal and mechanical analysis in a dam, it is necessary to use numerical methods that allow to determine the behavior of the concrete submitted to different types of stresses. Currently, these methods are calculated using Numerical computer programs based on the finite element method (FEM), used satisfactorily to calculate displacements, stresses and deformations in a structure over time [4].

In this work, we intend to implement a methodology that allows determining the temperature distribution in the F-5/6 block thermal-transient simulation.

1.1 Heat Transmission Mechanisms

The heat transfer between two bodies happens in a decreasing way until reaching the thermal balance between both bodies, respecting the principle of energy conservation. In a thermal analysis is important to know the means of transfer and distribution of heat, to determine the amount of energy transmitted or dissipated in a certain time period. There are three forms of heat transfer between systems have different temperatures: (i) conduction; (ii) convection and (iii) radiation [5].

In this work, the surface thermometers temperatures was used as border temperatures of the numerical model. Thus it's considered the temperatures presented in those thermometers are the result of the combination of these three forms of heat transmission occurs on the surface of the dam.

The conduction is a process with greater importance in solids than in liquids and gases; because the heat transfer happens through the direct contact between two bodies without movement through a molecular interaction [7]. One of the purposes of thermal analysis by conduction in a structure is to know the temperature distribution in the environment, arising from the thermal conditions existing at the borders. Once the temperature field is defined, it is possible to determine the heat flow by conduction at any point using Fourier's law, described in equation 1. In addition, it is possible to carry out the verification of its structural integrity, using the determination of thermal stresses, contraction, expansion and displacements [4].

According to Fourier's Law, which governs thermal conduction, the heat flow (q) is given by eq. (1) presented below:

$$q = -KA\frac{\Delta T}{\Delta x} \tag{1}$$

where k is the thermal conductivity coefficient of the material, A is the area perpendicular to the heat flow; ΔT is the temperature difference between the extremities, and ΔX is the thickness or distance between the extremities.

1.2 Solution of the thermal problem by MEF

Currently, there are different numerical methods for the calculation of thermal problems in structures, the finite element method (FEM) being one of the most used since it is a numerical technique that allows the determination of the solution of different equations, obtaining mainly the evolution in time or space of the variables involved in physical problems.

2 Case study: Hollow gravity block of the ITAIPU Hydroelectric Power Plant

The present work describes the thermal analysis applied to the hollow gravity block F-5/6, located in **Figure 2**. This is one of the key blocks of the dam, presenting a large number of monitoring instruments. In this way, it is possible to verify and validate the values obtained in the simulations with the data recorded by the instruments.

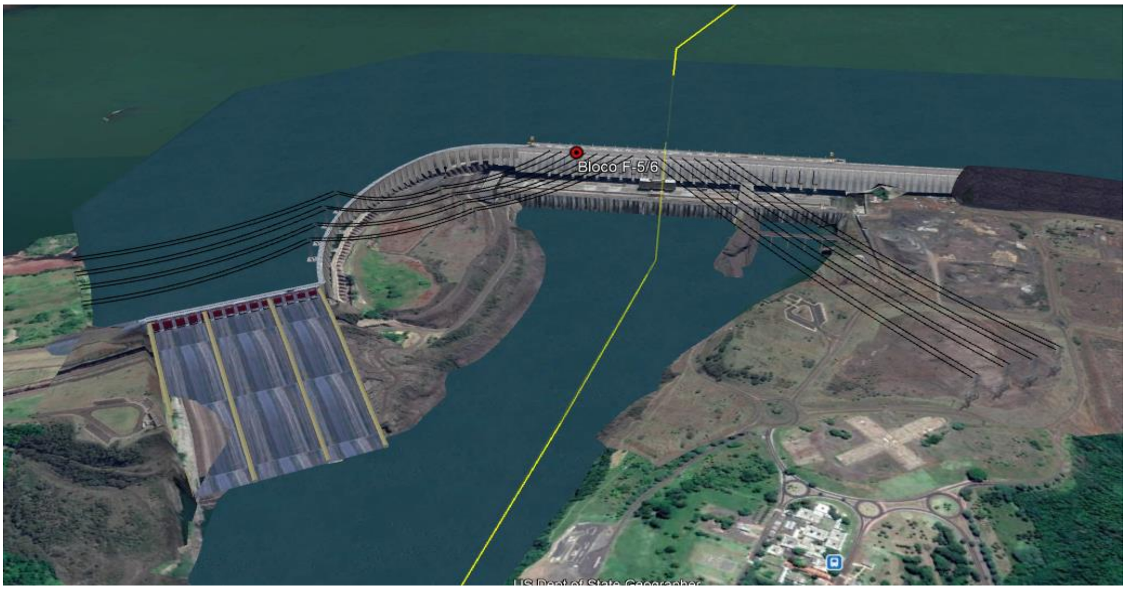


Figure 2. Location of block F-5/6 at the ITAIPU Dam.

2.1 Simplified block modeling

For the three-dimensional modeling stage of the block F-5/6, the geometric designs of the dam available in the Technical File System (SAT) were used. The block was modeled by monoliths following the construction plans.

2.2 Elaboration of the numerical mesh

After the geometry was completed, the domain was discretized. The numerical mesh made for this structure consists mainly of hexahedral elements as shown in **Figure 3**. This mesh was made by sections determined from the different cuts made in the geometry in order to obtain regular sections that would allow the generation of a better quality of the mesh.

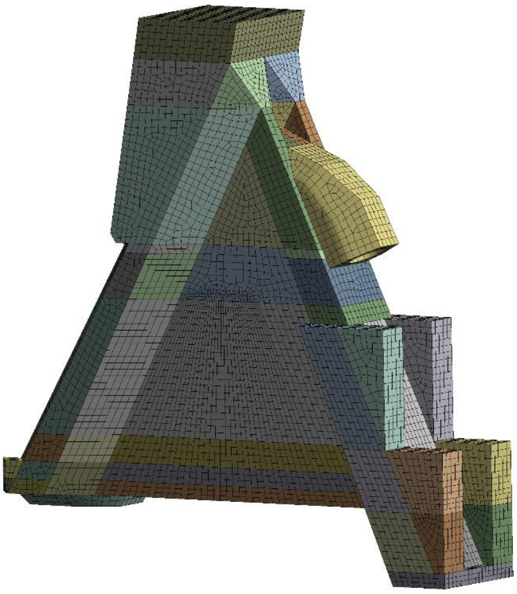


Figure 3. Finite element block discretization.

2.3 Data interpolation

The data recorded by the instruments installed in block F-5/6 were obtained in the management system of the dam.

Since the temperature measurements recorded on the thermometers are not periodic, it was necessary to perform an interpolation of the data using the cubic spline polynomial interpolation method, using the MATLAB program. Thus obtaining an estimate of the daily temperatures for each instrument.

2.4 Definition of the thermometers to be used in the simulation

As the F-5/6 block does not have surface thermometers on the downstream face, surface thermometers belonging to adjacent blocks were adopted in order to obtain the border temperature of this region.

Table 1 and **Table 2** show the elevations of the external and internal thermometers used in the thermal model.

Table 1. External thermometers used for the implementation of the model.

Instruments	Block	Elevation	Location
TS-F-01	F-5/6	145,25	Upstream
TS-F-02	F-5/6	100,25	Upstream
TS-F-12	F-19/20	50,25	Core
TS-F-13	F-19/20	50,25	Core
TS-D-903	D-54	187,60	Upstream
TS-D-904	D-57	200,30	Upstream
TS-D-005	D-57	198,00	Downstream

Table 2. Internal thermometers of block F-5/6 to validate the results.

Instrumentos	Bloco	Cota	Localização
TI-F-01	F-5/6	100,25	Upstream
TI-F-02	F-5/6	100,25	Core
TI-F-03	F-5/6	100,25	Downstream

2.5 Material properties

Table 3 shows the mechanical and thermal properties of the concrete of the block F-5/6, obtained from laboratory tests.

Table 3. Propriedades do concreto adotadas para o bloco F-5/6.

Properties		**Value**	**Unit**
Mechanics	Elasticity Module (E) - Static Analysis	35000	MPa
	Elasticity Module (E) – Dynamic Analysis	42000	MPa
	Poisson (ν)	0,2	-
Mechanical / Thermal	Density (ρ)	2400	kg/m^3
Thermal	Specific Heat	921,096	$Jkg^{-1}K^{-1}$
	Thermal Conductivity	1,99	$Wm^{-1}K^{-1}$
	Thermal expansion coefficient	$9x10^{-6}$	C^{-1}

For validation of all analyzes performed, the value of the elasticity module used was 35,000 MPa for static analyzes and 42000 MPa for dynamic analyzes (20% increase in the static elasticity module due to the increase in stiffness presented by the concrete in the dynamic tests).

2.6 Boundary conditions adopted

Figure 4 shows the thermal boundary conditions adopted for block F-5/6 and the respective faces adopted for each thermometers according to their installation level.

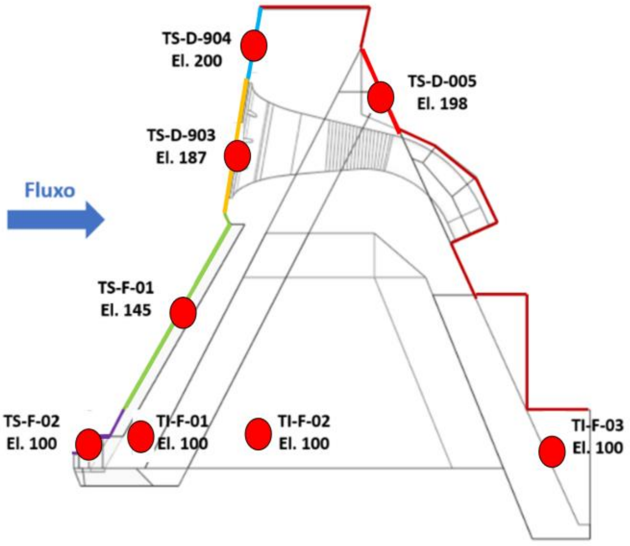
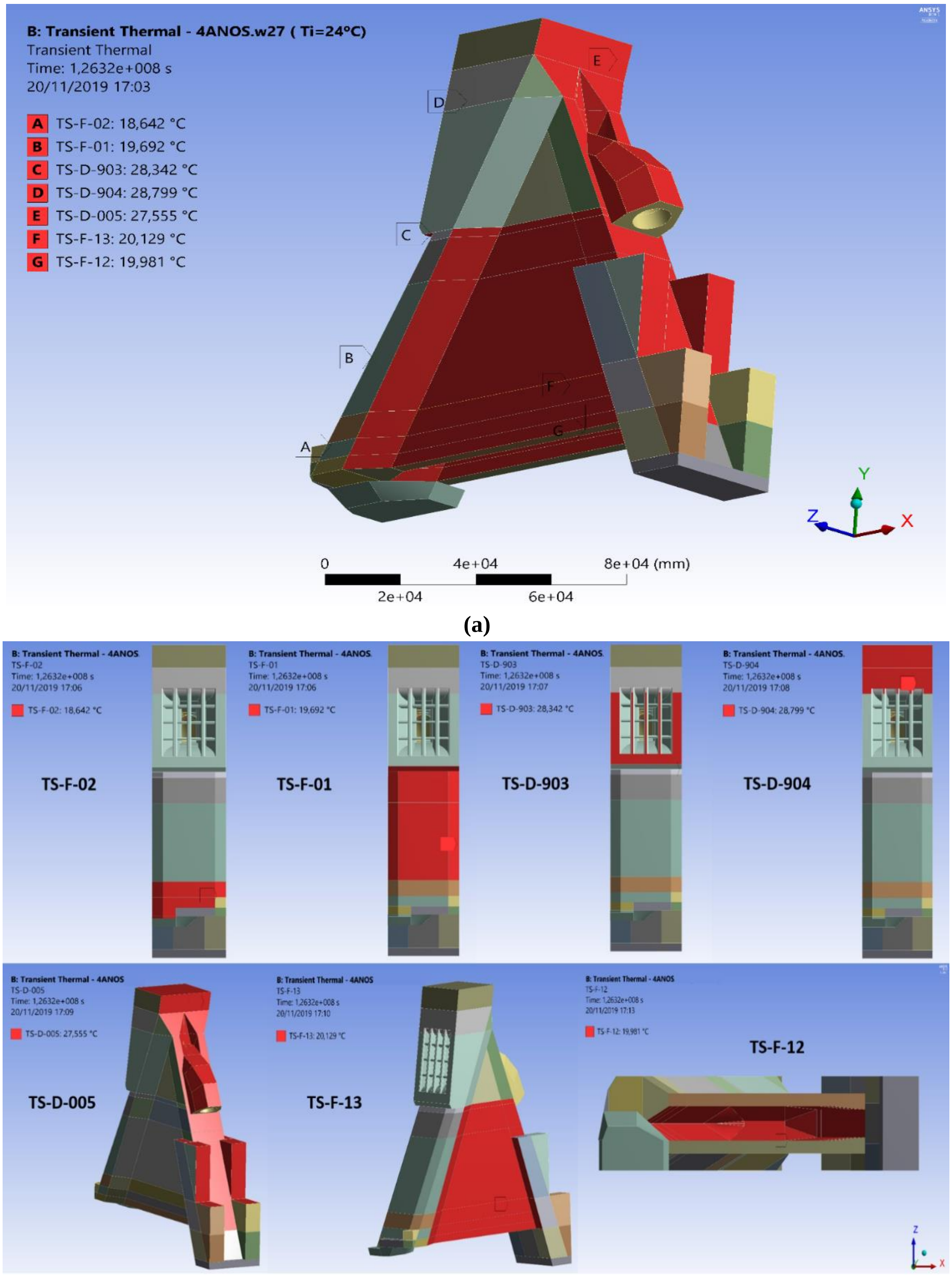


Figure 4. Elevation of external and internal thermometers used in the thermal model.

Several simulations were carried out to determine the best area of influence for each surface thermometer by checking the model's internal temperatures compared to the internal thermometers. **Figure 5** shows the faces adopted for each surface thermometer in the computational model.



(a)

(b)

Figure 5. Boundary conditions adopted in the thermal model (a); Defined areas for each of the surface thermometers (b).

2.7 Application and validation of the thermal model

For the transient thermal analysis, a period of 4 years (1982-1986) was adopted, considering intervals equivalent to one day. Therefore, 1462 steps were analyzed, subdividing each one in a range of 4 to 24 substeps to obtain convergence.

The validation of the model was performed by comparing the temperatures of the numerical model and the temperature of the internal thermometers, whose location is shown in **Figure 6**.

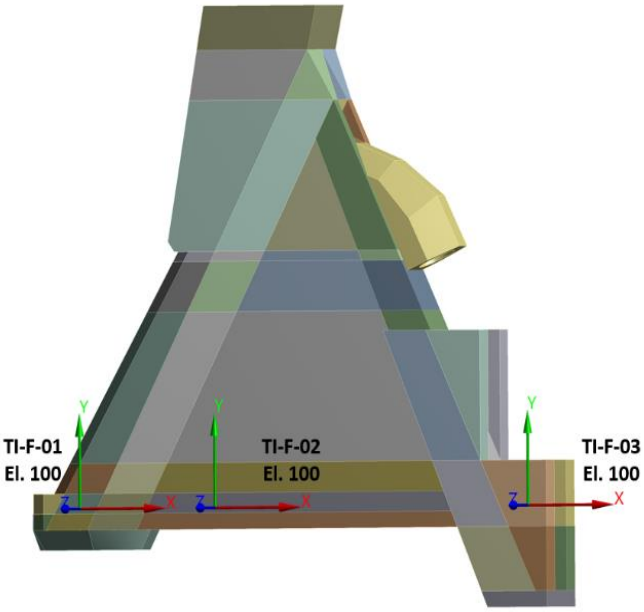


Figure 6. Test points located at the location of the internal thermometers of block F-5/6.

After the simulation process was completed, a study was carried out to validate the thermal model using the Mean Absolute Percentage Error (MAPE), which allows determining the approximation of the results obtained in the numerical simulation with the data recorded on the thermometers.

Such indicator is obtained from the following equation, eq (2):

$$MAPE[\%] = \frac{\sum_{i=1}^{n}\left|\frac{X_i - X'_i}{X_i}\right|}{n} \tag{2}$$

where Xi represents the interpolated temperatures, X'i the temperatures obtained in Ansys, and "n" the total number of days analyzed.

After conducting several simulations, it was realized a area influence thermometers comparations to achieve a better temperature distribution, as well as to obtain a closer approximation between the results. In **Figure 7**, it can be seen that the average absolute percentage error for the three internal thermometers was less than 10%.

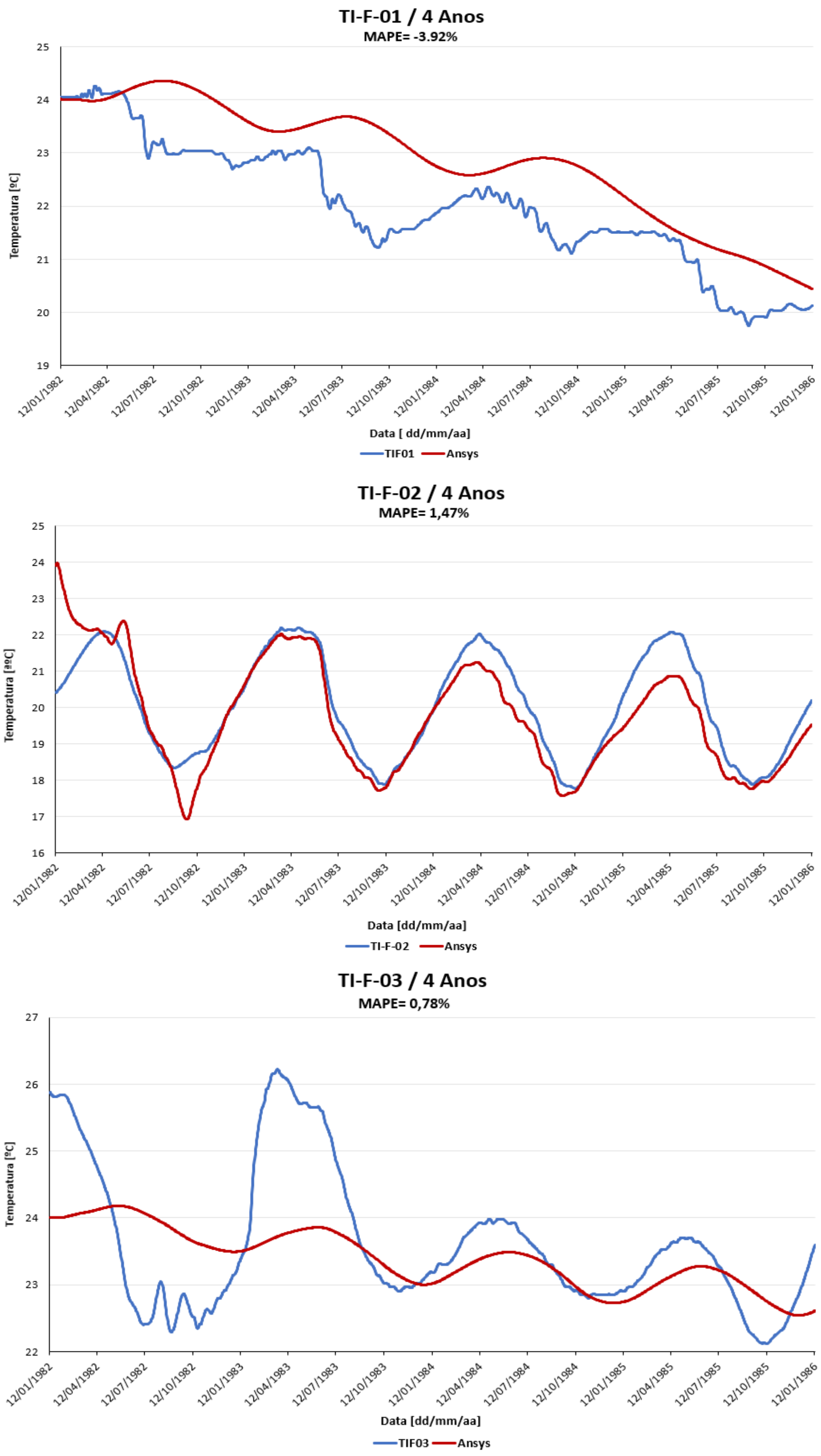
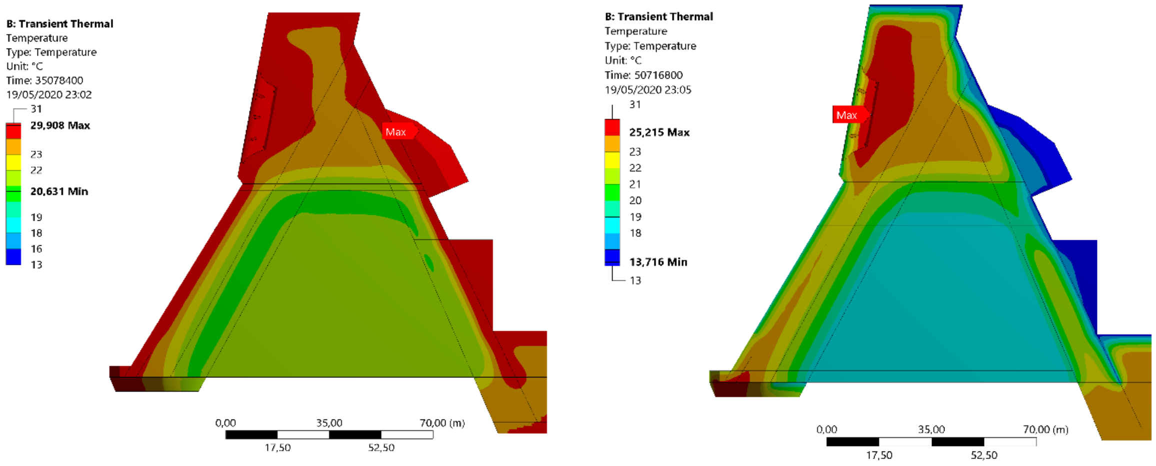


Figure 7. Comparison of the temperatures recorded in the internal thermometers present in block F-5/6 (TI-F-01, TI-F-02 and TI-F-03, respectively) with those obtained in Ansys.

2.8 Results obtained

Figure 8 shows the temperature distribution in block F-5/6 after the transient thermal simulation for the summer and winter seasons during the years 1983 to 1985.



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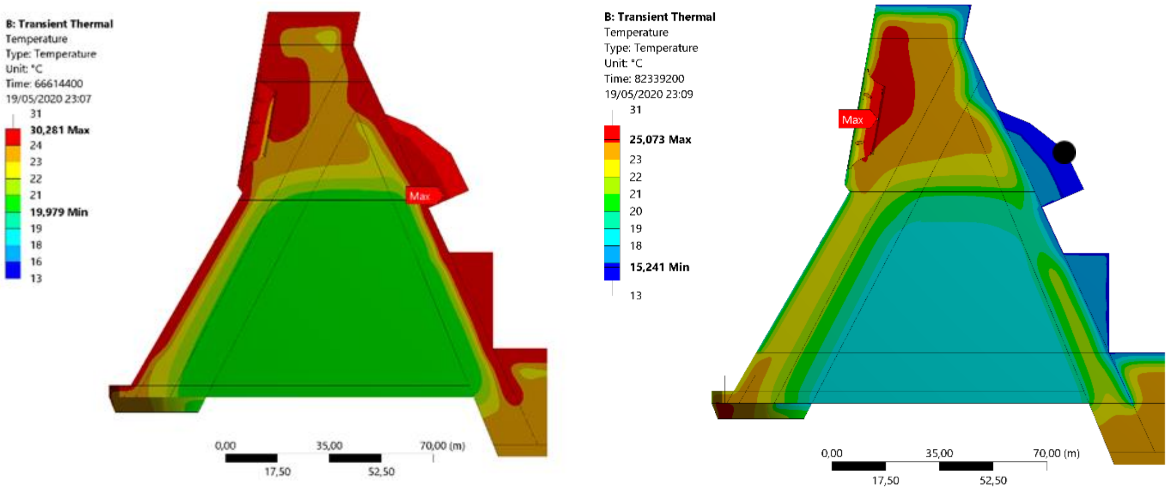
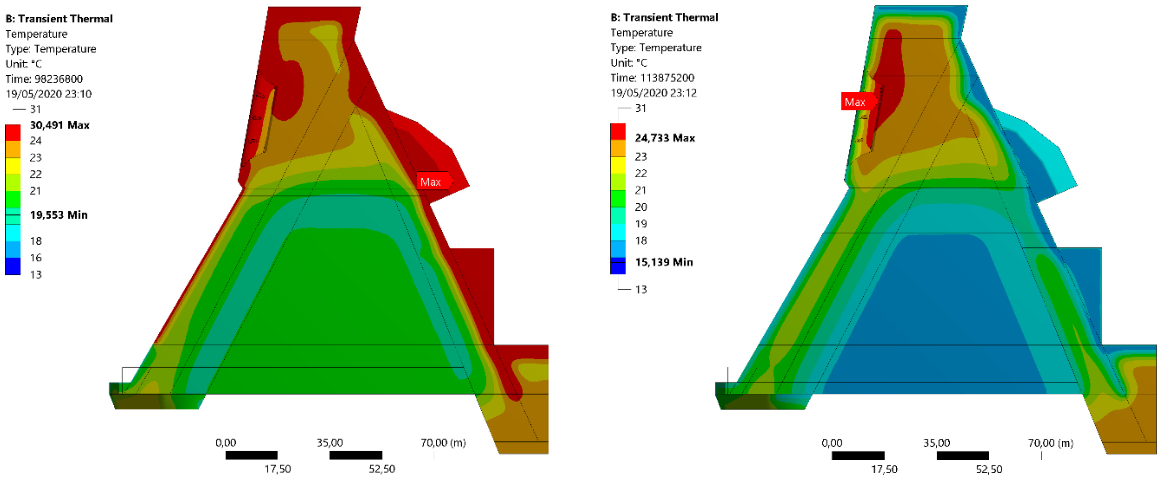


21/02/1984 21/08/1984



21/02/1985 21/08/1985

Figure 8. Temperatures distribution in block F-5/6 during the summer and winter seasons from 1983 to 1985.

3 Conclusions

The Mean Absolute Percentage Error (MAPE) is an indicator that measures the size of the absolute error in percentage terms and can be considered satisfactory when it is less than 10%. Therefore, the model carried out in this work was considered valid because it obtained lower values of MAPE at 10% for the three internal thermometers as shown in Figure 10, the values were 3.92% for TI-F-01, 1, 47% for the TI-F-02 and 0.78% for the TI-F-03. In the results of temperature fields, it can be observed during the summer the block reached temperatures close to 30°C on external faces, but inside, the temperatures varied between 19 and 21°C. In winter, the opposite happens, it has temperatures that vary from 13 to 15°C outside and between 24 and 26°C inside. With error values below 10% obtained in all internal thermometers, it is considered that the choice of surface thermometers as well as their extent of influence are satistories to represent the thermal behavior of the structure.

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References

[1] P.H.A. Oliveira. Hydrogeological problems in dams involving the tubular retroerosion mechanism. Graduation thesis (Graduation in Geology) – Federal University of Rio de Janeiro, Rio de Janeiro, Brazil, 2012.

[2] ITAIPU: Hydroelectric Power Plant – Engineering aspects. Foz do Iguaçu: Itaipu Binacional, 2009.

[3] E. Possan. Dam Safety Course. Module I – Dams: Legal, technical and socio-environmental aspects. 2015. Available in: <https://www.researchgate.net/publication/326468134_BARRAGENS_DE_CONCRETO>. Accessed on: April 30, 2020.

[4] T. Hickmann. Analysis of the effect of seasonal thermal variation in buttresses Dam. PhD thesis (PhD in Numerical Methods in Engineering) – Federal University of Paraná, Curitiba, Brazil, 2016.

[5] P.B.C. Fonseca. Thermo-mechanical analysis of the pillars of a flood unloader. Dissertation (Master in Civil Engineering - Specialization in Structures) – University of Porto, Porto, Portugal, 2014.

[6] P.H.D. Santos. Heat transfer 2: Introduction to convection. 2013. 54p. Class notes. Federal Technological University of Paraná, Ponta Grossa, Brazil.

[7] A.M. Domingo. Notes of heat transmission. 2018. 83p. Higher Technical School of Architecture – UPM, Madrid. Available in: <http://oa.upm.es/50949/>. Accessed on: May 5, 2020.