Modeling and Simulation of Heat Transfer in a Cold Wall Vacuum Furnace Considering Geometric Optimization of Heating Elements

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Abstract. This work proposes the thermal sizing of a furnace, starting from a review of the state of the art of furnaces with similar characteristics and thus defining the general concept. Then, a transient state analytical model is developed that allows to know the necessary power for the heating elements, the temperature profile on the walls of the furnace, the amount of insulation needed to protect internal components, and other related specifications. Due to the parameterization of the model, it is possible to perform sensitivity analyses to verify the behavior of the system with the variations of thermophysical properties of interest.

Keywords: Heat treatment furnace · modelling · heat transfer

1 Introduction

The Colombian energy matrix is mainly based on the generation in hydroelectric and thermal power plants, for which large volume and weight turbines and parts are required. Empresas Públicas de Medellín provides electricity in Antioquia through 25 hydroelectric plants, 1 thermal power plant, and 1 wind power plant. The need for thermal treatment furnaces to repair key elements in these plants leads to a project to design a controlled argon atmosphere thermal treatment furnace with an operating temperature of 1200 °C, pressures from 1×10^{-4} torr to 1.2 bar, and temperature control of ±10 °C. A typical furnace design is used for reference. This work proposes the thermal sizing of the furnace through a review of similar furnaces and the development of an analytical model to determine the power of heating elements, wall temperature profile, insulation needs, and other specifications [1, 3]. The model also allows for sensitivity analyses to evaluate system behavior with changes in thermophysical properties.

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2 Loading Scenario

In this furnace, it is of special interest to treat and repair parts of the thermal power plants in Antioquia-Colombia. Therefore, the main load scenario of the system corresponds to the first stage nozzle presented in Fig. 1, this piece operates in La Sierra thermal power plant in the department of Antioquia in Colombia where up to 460 MW of power is produced.

Fig. 1. First stage nozzle (thermal power plant).

This piece is made of a nickel-based alloy (Inconel 625), has a diameter of 2650 mm and a mass of 2500 kg. The treatment must be done by following heating and cooling rates of 100 °C/h and a temperature during the holding of 1200 °C while also maintaining control in critical areas of the piece of ±10 °C to prevent breakages in the joint areas.

3 Thermal Modelling

3.1 Hot Chamber Radiation

Most thermal treatments in the furnace occur under vacuum conditions, where heat transfer from heating elements to the load occurs mainly by radiation. A common approach in analytical models is to treat the elements as black bodies and use the Stefan-Boltzmann law for calculation, which is quick but not accurate enough. A radiation heat transfer model is implemented in the hot chamber, considering view factors that represent real thermal radiation distribution. To calculate view factors, a simplified CAD model is entered into finite element software and calculated during the configuration phase.

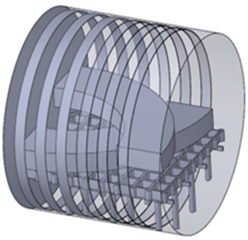

Fig. 2. Simplified CAD for radiation view factors calculation.

Figure 2 shows the simplified CAD model used, which utilizes symmetry and includes key elements and the main load scenario to reduce computational cost.

Finally, the average view factors on the surfaces of interest are obtained as shown in Fig. 3. This graph only reflects the values obtained for the load, however, the view factors corresponding to all the components that will be subjected to radiation within the furnace such as the loading fixture, the covers, the cylindrical wall, and others are obtained.

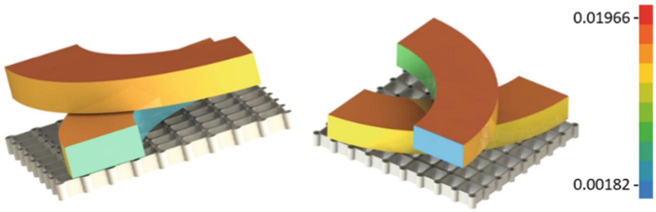

Fig. 3. Average radiation view factors in load.

3.2 Heat Transfer Across the Furnace

As previously mentioned, it is necessary to know the thermal behavior of the insulation shell and thus make decisions regarding the components of the system [5]. To do this, a heat transfer model by conduction through the cylindrical surface and the cover of the furnace is proposed. A scheme that shows the layers to be modeled is presented in Fig. 4.

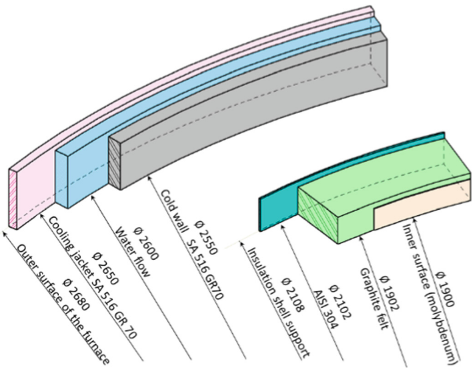

Fig. 4. Schematic of the furnace layers.

The analytical model has two key limitations. First, the heating element power is a variable parameter that can be adjusted to meet the system's heating requirements. Second, the cooling section on the furnace's outer layer must maintain temperatures within acceptable limits to ensure the system's tightness, protect control elements and avoid the use of special refractory materials. The equations for the system's energy balance and radiosity consider average temperatures for internal surfaces and the load, with a material mesh for the insulation shell. The equations for the load's energy balance and the general equation for the system radiosity are presented [2, 4].

$$mC_p\frac{dT}{dt} = QF_{ri} + A_i\sum_{j=1}^{n}\left(F_{ij}\left[J_j - J_i\right]\right) \tag{1}$$

$$Ji = \sigma\epsilon_i {T_i}^4 + \sum_{j=1}^{n} F_{ij}J_j(1-\epsilon_i) \tag{2}$$

where m is the mass of the load, Cp is the heat capacity of the piece, QF_{ri} is the product of the power and the view factor from the heating elements to surface i, A is the area according to the surface, and $F_{ij}[J_j - J_i]$ is the product of the view factor from one surface to another and the difference of radiosity (which represents the heat emitted and reflected), σ is the Stefan-Boltzmann constant and ϵ_i the emissivity of each surface.

4 Results

Initially, a steady-state analysis is carried out with the model already proposed and restricting the temperature of the load to 1200 °C which corresponds to the holding stage, with this it is possible to determine the temperature profile that the furnace will have and the power that corresponds to 146 kW, this value refers to the power necessary to supply the system losses in the stationary or holding stage. The behavior mentioned can be appreciated in Fig. 5.

It can be seen in Fig. 5 that the stabilization of the system with the holding power (steady state) is achieved in a time of around 25–30 h, this makes the heating rates established in the furnace specifications not met. To achieve the required rates, a transient state analysis is carried out with the variation of the system power.

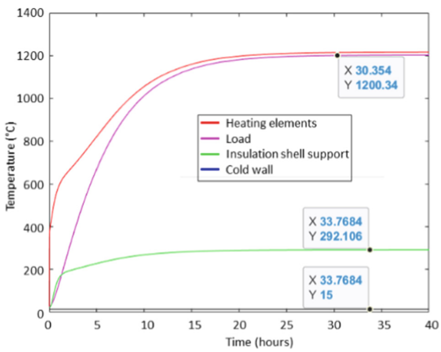

Fig. 5. Steady state temperature profile.

To meet the heating and cooling time requirements, an iterative analysis is performed using the power parameter. Figure 6 shows the three stages of thermal treatment (heating, holding, and cooling) for key elements in the furnace, such as the heating elements, load, insulation support (stainless steel support), and outer wall. The main advantage of the model is its ability to evaluate the furnace's thermal behavior over an extended period (80 h) without extensive computing and simulation. The model provides average temperatures, but not detailed profiles. After consolidating the model, the optimum configuration (180 mm separation, 890 mm internal radius) is selected based on energy efficiency.

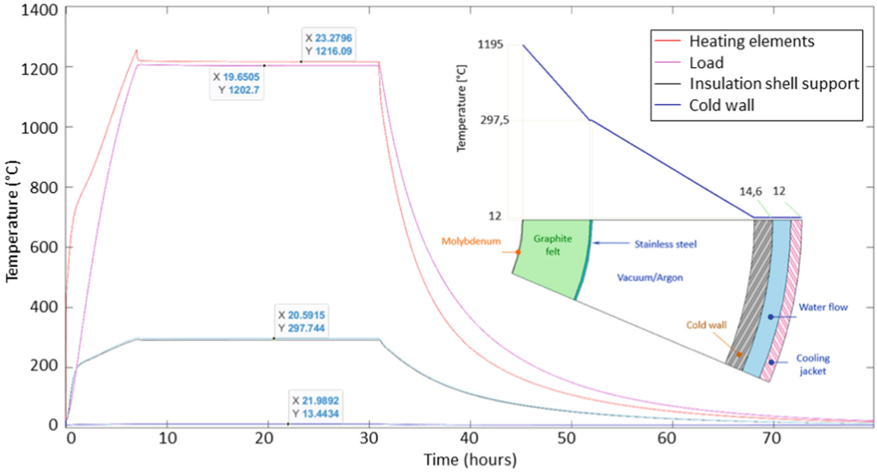

Fig. 6. Transient state temperature profile.

Figure 7 shows the temperature profile of a simulation carried out on conventional finite elements software with the same properties. The outer surface of the insulation shell is 400 °C, higher than the analytical model's result of 292 °C, due to the specific geometries like the load columns that increase heat transfer in the outer zone. Figure 7 shows the average temperatures on the outer surface of the furnace with the same water parameters. The blue values mostly match the analytical model. The argon inlet pipe causes a hot zone where the water does not circulate well, but the proposed model still offers good results for average temperatures, mass, energy balances, etc.

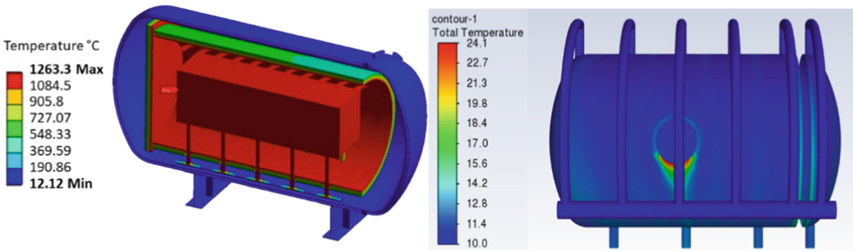

Fig. 7. Validation by a conventional finite elements software.

5 Conclusions

The study develops a model for predicting the thermal behavior of a cold-wall vacuum furnace, which has reliable results and faster computation for transient simulation. The model enables fast parameter changes for easier system design. Although it does not evaluate specific geometry, the results are consistent with reality and validated with conventional software, making it useful in design.

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