

Research Article

Criterion Relaxation in Physical Simulation for Electric Melting Glass Furnace

Ning Wei, Luo Lida, Chen Xiaojun and Wang Qingwei
 Research Institute of Donghua University, Shanghai, 201620, China

Abstract: All electric glass melting technologies are developed based on the physical simulation and mathematical simulation. This technology has been widely applied due to its superior performance. However, its application is subjected to certain restrictions because it still has some problems yet. In order to further develop electric melting technology, we have to find the solutions from the physical and mathematical simulation. This study briefly introduces the application of physical simulation and dimensionless criteria relaxation for electric melting glass furnace.

Keywords: Dimensionless criterion relaxation, electric melting furnace, physical simulation

INTRODUCTION

As a kind of traditional architectural material and daily product, glass is widely used around the world. The development of glass manufacturing technology is the witness to the progress of the times (Mcconnel and Goodson, 1979). The glass melting furnace, which is the essential equipment of glass production, develops increasingly along with the time progress (Stanek, 1977). As far as the recent situation is concerned, the evolvement from traditional flame tank furnace to the modern electric melting glass furnace is of great significance for energy-saving and emission reduction (Petr and Josef, 2004). Unfortunately, due to its very complicated physical, chemical and transmission (heat and material) process, Qi *et al.* (1994a, b) presented it was extremely difficult to study on electric field and flow field (flow status). It encourages the glass melting engineers to find a convenient and shortcut way to conduct observation, investigation and then optimize the furnace design eventually (Labar and Djeghader, 2009).

There are three main research methods on glass melting furnace (Mcconnel and Goodson, 1979):

- On-site measurement of glass furnace
- Physical simulation
- Mathematical simulation

The study will mainly introduce the physical simulation on electric melting glass furnace design.

THEORETICAL BASIS OF PHYSICAL SIMULATION, GOVERNING EQUATION AND BOUNDARY CONDITION

Three theorems of similarity theory: The theoretical bases of physical simulation are the three theorems of

similarity theory (Mase and Oda, 1980). The following ways for physical simulation were adopted by the authors. Where heat transfer differential equation is:

$$C_a a = -\frac{C_\lambda}{C_t} \frac{\lambda}{\Delta t} \frac{C_l}{C_l} \left(\frac{\partial t}{\partial n} \right)_{n \rightarrow 0} \quad (1)$$

In Eq. (1), C is proportional constant of various physical parameters, i.e., similarity constant. The typical Nusselt Number (Nu value) can be derived by differential equations (Fig. 1):

$$C \alpha = \frac{C \lambda}{C t} \cdot \frac{C t}{C l} \rightarrow \frac{\alpha l}{\lambda} = Nu \quad (2)$$

$$Nu = \frac{\alpha l}{\lambda} = \frac{\frac{l}{\lambda}}{\frac{1}{\alpha}} = \frac{\alpha \Delta t}{\frac{l}{\lambda}} = \frac{-\frac{\partial t}{\partial x}}{\frac{l}{\lambda}} \quad (3)$$

From the conversion of the equations it can be known that:

- Nusselt Number indicates the ratio of heat resistance at boundary layer to heat resistance of heat convection.
- Δt reflects the ratio of heat convection value to heat conduction value at boundary.
- The relation of temperature gradient at boundary layer to average temperature gradient derived by characteristic dimension.

Then the similarity constant was introduced into heat conducting differential equations.

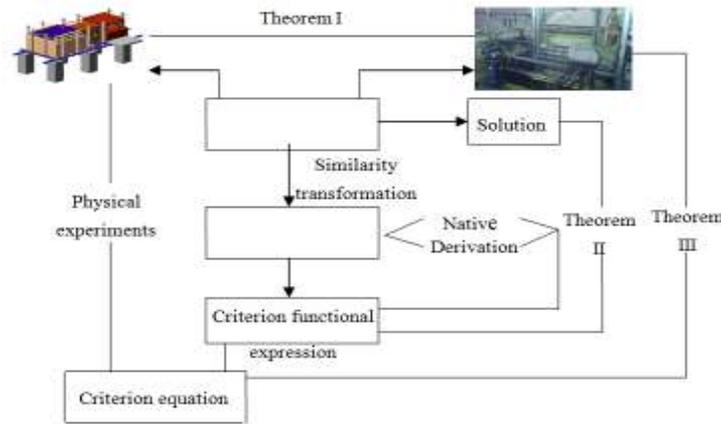


Fig. 1: Model to derive typical Nusselt Number (Nu value)

From the above equations, it can be seen that Harmonic Number Ho shows the instability of fluid flow. The value should keep constant when the flow is stable. Note “o” indicates that the Number value is related to time; the Peclet Number Pe reflects the relation between fluid velocity field and temperature field; Fourier Number Fo indicates the instability of heat transfer:

$$\frac{C_t}{C_\tau} = \frac{C_t C_\omega}{C_l} \rightarrow \frac{\omega_z}{l} = Ho \quad (4)$$

$$\frac{C_t C_\omega}{C_l} = \frac{C_a C_t}{C_l^2} \rightarrow \frac{\omega l}{a} = Pe \quad (5)$$

$$\frac{C_t}{C_\tau} = \frac{C_a C_t}{C_l^2} \rightarrow \frac{a\tau}{l} = Fo \quad (6)$$

Then the similarity constant is introduced into motion differential equations:

$$C_\rho \rho \frac{\partial t}{\partial \tau} + \frac{C_t}{C_l} \frac{\partial t}{\partial x} C_\omega \omega_x + \frac{\partial t}{\partial y} \omega_y + \frac{\partial t}{\partial z} \omega_z \\ = C_\rho \rho C_g g_x - \frac{C_p}{C_l} \frac{\partial p_x}{\partial x} + C_\mu \mu \frac{C_\omega}{C_l^2} \left(\frac{\partial^2 \omega_x}{\partial x^2} + \frac{\partial^2 \omega_x}{\partial y^2} + \frac{\partial^2 \omega_x}{\partial z^2} \right) \quad (7)$$

This equation is based upon Newton's second law reflecting the relations amongst mass force, pressure and viscous force in glass melt.

Basic condition of simulation: Based on similarity principle and following the above basic conditions, a study on physical simulation which satisfies the following conditions was carried out for fluid dynamics in glass tank furnace by the authors:

$$\beta_M \Delta t_M / \beta_E \Delta t_E = \text{item}^* \quad (8)$$

$$Ga = [gl^3/v^2]_M = [gl^3/v^2]_E = \text{item} \quad (9)$$

$$Re = [\omega l/v]_M = [\omega l/v]_E = \text{item} \quad (10)$$

where,

- β = Volume expansion coefficient of fluid, $^{\circ}C^{-1}$
- Δt = Temperature difference, $^{\circ}C$
- g = Gravitational acceleration, m/s^2
- l = Dimension of corresponding part, m
- v = Kinematic viscosity, m^2/s
- ω = Velocity of fluid, m/s

SIMILARITY CRITERION RELAXATIONS

Considering the complicated system and multiple changes of complex variables functions, the typical Nusselt Number was selected for discussion, in order to find the solution of convective heat transfer coefficient so as to simulate convection field. Functional expression of Nusselt Number is:

$$Nu = f(Ho, Fo, Pe, Fr, Eu, Re, Rr, Ga, Gr, l/l_0)$$

To simplify calculation, the following settings were adopted:

- Establishing steady flow to eliminate Ho and Fo
- For geometrical similarity system, the l/l_0 can be ignored
- Fr can be eliminated by ignoring the influence of gravitational field
- By ignoring the pressure field, Eu can be eliminated due to the fact that Gr already includes Ga and Pr includes Pe , therefore, $Nu = f(Re, Rr, Gr)$
- For natural convection system $Nu = f(Gr, Fr)$, for forced convection system, $Nu = f(Re, Pr)$

Strict model criteria: The most strict similarity criteria should involve geometric similarity and Re , Fr , Gr , Po and Nu . It is noticed that due to $Pe = Re \cdot Pr$ and $Fr = Ga \cdot Re^2$, when a special criterion appears the different dimensionless treatment method might change equations and pass variables.

Table 1: Comparison of various similarity criteria in physical simulation of furnace

Model parameters	Small furnace	Large furnace	Small furnace	Large furnace
Hm/cm	1.27	2.54	30.48*	60.96*
μm	1.17	1.17	1.17	1.17
Pm mL/min	0.14	1.40	3.00	15.30
Wm/Watt	180.00	2257.00	0.38	19.20
$(\Delta T) \text{ m}/^\circ\text{C}$	1.02×10^4	1.02×10^4	1.00	8.00
$T_R / ^\circ\text{C}$	20.00	20.00	20.00	20.00
$T_f / ^\circ\text{C}$	20.00	20.00	20.00	20.00
$T_m / ^\circ\text{C}$	1.022×10^4	1.022×10^4	21.00	28.00
Em/V	66.00*	212.00*	1.87*	6.12*
Yi/cm	0.00	0.00	15.24	7.62

*: Free choice within the limited range; H: A particular characteristic dimension

Table 2: The maximum deviation of dimensionless criteria between model and furnace

Dimensionless criterion	Influence on μ, K	Maximum evaluated deviation of model
Re	$1/\mu^2$	20%
Pr	μ/K	40%
Pe	$1/K$	20%
Gr	$1/\mu^2$	40%
Ra	$1/\mu K$	$\cong 0\%$
Ga	$1/\mu^2$	40%
Nu	$1/K$	20%

Large value of Pr criteria: As far as glass is concerned, the order of Pr criterion is $10^2 \sim 10^5$ and its independent influence can be ignored. In this case the related dimensionless criteria are $Re*Pr$, $Ga*Pr$, $Gr*Pr$, Po , NuB and NuS .

Ga criterion: The gravitational effect in glass furnace may change the static pressure field of the fluid. If our intention is not to simulate the effect of pressure, then Ga criterion or Fr criterion is not necessary to be taken into account. Therefore only $Re*Pr$, $Ga*Pr$, $Gr*Pr$, Po , NuB and NuS criteria should be satisfied.

The comparison of various similarity criteria: The various similarity criteria can be compared in given simulating fluid and simulated furnace (Table 1).

The effect of temperature difference on physical properties leads to the maximum evaluated deviation of various dimensionless criteria between model and furnace (Table 2).

RESULTS AND DISCUSSION

Re, Fr, Pr, Gr, Po, Nu are a group of most strict similarity criteria. In fact, they are very difficult to be satisfied simultaneously:

- If the Fr is ignored, then the choice freedom for the model increases, so that the model size and temperature difference may be within the allowed

and reasonable range. Pulling of simulating fluid is able to be realized for large furnace; however, for small sized furnace the pulling volume is also smaller. Similarly, for small sized furnace, the power input is smaller and insulating layer is thicker. Thus this kind of model with ignored Fr criterion is more suitable for large furnace.

- If the Pr criterion regarded as an independent criterion is ignored, then the choice freedom increases. For small sized furnace, it improves power input condition and the pulling volume keeps the same as before, only the insulating layer is thicker.
- If Ra, Pe, Ro, Nu criteria are adopted and the temperature of the simulating fluid increases in accordance with the required heat for heating it, then the similarity criteria are allowed to increase pulling volume. It is helpful for enhancing pulling volume of small furnace.

It can be seen that when different electric melting glass furnaces are simulated, the relaxation of similarity criteria could be applied according to their various situation. Thus the electric melting glass furnace can be actually simulated effectively and exactly, so that the results are satisfactory enough.

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