Development of Empirical Correlation for Thermal Fatigue Life Cycle Prediction

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Abstract: ***Furnaces are most commonly used for melting of Iron and its various alloy materials. Induction furnaces are using electric power supply so they are more beneficial as no fuel is required. It is an extremely critical to find life span or life cycle of Induction Melting Furnace Wall under thermal load change conditions. The low cycle thermal fatigue life time L is depended upon various parameters like thickness of induction furnace refractory wall t, density of refractory material ρ, inside film co-efficient h_I outside film co efficient h_o, thermal expansion coefficient α, inside temperature T_I, outside temperature T_o, specific heat of refractory material C, elasticity constant E, ultimate strength S, thermal conductivity of refractory material k, Volume V, time period of melting cycle τ. An expression for thermal fatigue life time of induction furnace melting wall is derived by dimensional analysis using bunkingham's π theorem. Then the empirical correlation is derived from the data available from theory as well as experimental and numerical results.***

Keywords: - Induction Furnace, Heat Transfer, Empirical Correlation, Life Cycle Prediction

I. INTRODUCTION

The furnace is a system used for melting the metals for casting or heating of materials to changing form and its size like rolling, forging etc. It is also used for change any material properties of the metals like annealing or normalizing processes. Generally, furnace is assessed into two types in keeping with generating approach of heat. It is combustion type and electric kind. In combustion kind of furnace usually used as fuel is oil and coal. Then electric type furnace known as induction furnace. If we want to solve heat transfer and thermal fatigue problems involving simple geometries with effortless boundary circumstance. It is solved by using analytical procedure but whilst it is intricated boundary circumstance than we cannot solve analytically. There are numerous approaches to obtains the numerical process of heat transfer problem consisting of finite difference approach, finite element method and boundary element approach.

II. LITERATURE SURVEY

The study on the distribution rule of temperature and thermal stress distribution and on the fatigue life comparison process for the refractory wall

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Is not going to lay foundation for the improvement acquaintance of on the thermal fatigue of this form of elements underneath thermal shock conditions of low cycle and excessive phase transition stresses but in addition presents amazing management for thermal fatigue failure.

A complete literature assessment on computational investigation on one of a kind of variety of furnaces is completed to be trained study trends. An overview is done on applications of distinct numerical approaches in heat transfer with its applications. Thermal fatigue evaluation of induction melting furnace wall is done for silica ramming mass. An evaluation is completed for study on induction heating. A evaluate is finished for metal forming analysis utilizing exceptional numerical approaches. Transient heat transfer analysis of induction furnace is done through utilizing finite detail evaluation. Thermal fatigue evaluation of induction furnace wall is finished for alumina ramming mass. Thermal evaluation of scorching wall condenser is done for home refrigerator using numerical process for temperature distribution. Optimization of wall thickness for minimal heat loss for induction furnace wall via finite detail evaluation. An assessment is finished on numerical evaluation of furnace. Thermal fatigue analysis of induction furnace refractory wall is finished for zirconia. Comparison of finite difference system and finite detail procedure is finished for 2 D transient heat switch predicament. Thermal fatigue analysis of induction furnace wall is completed for magnesia ramming mass. Evolved mathematical modelling of heat transfer is finished for induction furnace wall of zirconia. Advanced heat transfer analysis is completed for alumina based refractory wall of induction furnace. Also, specific Finite change procedure is used to find out temperature and thermal stress difference with respect to time. [1-38]

III. DEVELOPMENT OF EMPIRICAL CORRELATION

The functional relationship can be written is the following format.

$L = f\,(t, \rho, h_i, h_o, \alpha, T_i, T_o, C, E, S, k, \tau, V)$

Its general format becomes as following.

$F\,(L, t, \rho, h_i, h_o, \alpha, T_i, T_o, C, E, S, k, \tau, V) = 0$

Here, number of variables n = 14

Number of fundamental quantity m = 4

No. of π terms = n – m = 14 – 4 = 10.

Repeating variables:

1. geometry property – t
2. thermal property – T_i
3. fluid property – ρ
4. time variable – τ

$\pi_1 = t^{a1}\, T_i^{b1}\, \rho^{c1}\, \tau^{d1}\, k$
$\pi_2 = t^{a2}\, T_i^{b2}\, \rho^{c2}\, \tau^{d2}\, h_i$
$\pi_3 = t^{a3}\, T_i^{b3}\, \rho^{c3}\, \tau^{d3}\, \alpha$
$\pi_4 = t^{a4}\, T_i^{b4}\, \rho^{c4}\, \tau^{d4}\, E$
$\pi_5 = t^{a5}\, T_i^{b5}\, \rho^{c5}\, \tau^{d5}\, C$
$\pi_6 = t^{a6}\, T_i^{b6}\, \rho^{c6}\, \tau^{d6}\, L$
$\pi_7 = t^{a7}\, T_i^{b7}\, \rho^{c7}\, \tau^{d7}\, T_o$
$\pi_8 = t^{a8}\, T_i^{b8}\, \rho^{c8}\, \tau^{d8}\, S$
$\pi_9 = t^{a9}\, T_i^{b9}\, \rho^{c9}\, \tau^{d9}\, h_o$
$\pi_{10} = t^{a10}\, T_i^{b10}\, \rho^{c10}\, \tau^{d10}\, V$

Dimensions of different quantities are as per following.
L => $M^0 L^0 T^1 K^0$, ρ => $M^1 L^{-3} T^0 K^0$, k => $M^1 L^1 T^{-3} K^{-1}$, h_i => $M^1 L^0 T^{-3} K^{-1}$, C => $M^1 L^2 T^{-2} K^{-1}$, T_i => $M^0 L^0 T^0 K^1$, T_o => $M^0 L^0 T^0 K^1$, t => $M^0 L^1 T^0 K^0$, h_o => $M^1 L^0 T^{-3} K^{-1}$, α => $M^0 L^1 T^0 K^{-1}$, E => $M^1 L^{-1} T^{-2} K^0$, τ => $M^0 L^0 T^1 K^0$, S => $M^1 L^{-1} T^{-2} K^0$, d => $M^0 L^3 T^0 K^0$

Now 10 different π terms are derived from dimensional analysis.

1. $\pi_1 = t^{a1}\, T_i^{b1}\, \rho^{c1}\, \tau^{d1}\, k$
$\pi_1 = M^0 L^0 T^0 K^0 = [L]^{a1}[K]^{b1}[ML^{-3}]^{c1}[T]^{d1}[M^1 L^1 T^{-3} K^{-1}]$
Power of M: 0 = c1 + 1, c1 = -1
Power of L: 0 = a1 – 3c1 + 1, a1 – 3(-1) + 1 = 0, a1 = -4
Power of T: 0 = d1 – 3, d1 = 3
Power of K: 0 = b1 – 1, b1 = 1
$$\pi_1 = \frac{T_i\, k\, \tau^3}{\rho\, t^4}$$

2. $\pi_2 = t^{a2}\, T_i^{b2}\, \rho^{c2}\, \tau^{d2}\, h_i$
$\pi_2 = M^0 L^0 T^0 K^0 = [L]^{a2}[K]^{b2}[ML^{-3}]^{c2}[T]^{d2}[M^1 L^0 T^{-3} K^{-1}]$
Power of M: 0 = c2 + 1, c2 = -1
Power of L: 0 = a2 – 3c2, a2 – 3(-1) = 0, a2 = -3
Power of T: 0 = d2 – 3, d2 = 3
Power of K: 0 = b2 – 1, b2 = 1
$$\pi_2 = \frac{T_I\, h_I\, \tau^3}{\rho\, t^3}$$

3. $\pi_3 = t^{a3}\, T_i^{b3}\, \rho^{c3}\, \tau^{d3}\, \alpha$
$\pi_3 = M^0 L^0 T^0 K^0 = [L]^{a3}[K]^{b3}[ML^{-3}]^{c3}[T]^{d3}[M^0 L^1 T^0 K^{-1}]$
Power of M: 0 = c3, c3 = 0
Power of L: 0 = a3 – 3c3 + 1, a3 – 3(0) + 1 = 0, a3 = -1
Power of T: 0 = d3, d3 = 0
Power of K: 0 = b3 – 1, b3 = 1
$$\pi_3 = \frac{T_I\, \alpha}{t}$$

4. $\pi_4 = t^{a4}\, T_i^{b4}\, \rho^{c4}\, \tau^{d4}\, E$
$\pi_4 = M^0 L^0 T^0 K^0 = [L]^{a4}[K]^{b4}[ML^{-3}]^{c4}[T]^{d4}[M^1 L^{-1} T^{-2} K^0]$
Power of M: 0 = c4 + 1, c4 = -1
Power of L: 0 = a4 – 3c4 – 1, a4 – 3(-1) – 1 = 0, a4 = -2
Power of T: 0 = d4 – 2, d4 = 2
Power of K: 0 = b4, b4 = 0
$$\pi_4 = \frac{E\, \tau^2}{\rho\, t^2}$$

5. $\pi_5 = t^{a5}\, T_i^{b5}\, \rho^{c5}\, \tau^{d5}\, C$
$\pi_5 = M^0 L^0 T^0 K^0 = [L]^{a5}[K]^{b5}[ML^{-3}]^{c5}[T]^{d5}[M^1 L^2 T^{-2} K^{-1}]$
Power of M: 0 = c5 + 1, c5 = -1
Power of L: 0 = a5 – 3c5 – 1, a5 – 3(-1) + 2 = 0, a5 = -5
Power of T: 0 = d5 – 2, d5 = 2
Power of K: 0 = b5 – 1, b5 = 1
$$\pi_5 = \frac{T_i\, C\, \tau^2}{\rho\, t^5}$$

6. $\pi_6 = t^{a6}\, T_i^{b6}\, \rho^{c6}\, \tau^{d6}\, L$
$\pi_6 = M^0 L^0 T^0 K^0 = [L]^{a6}[K]^{b6}[ML^{-3}]^{c6}[T]^{d6}[M^0 L^0 T^1 K^0]$
Power of M: 0 = c6, c6 = 0
Power of L: 0 = a6 – 3c6, a6 – 3(0) = 0, a6 = 0
Power of T: 0 = d6 + 1, d6 = -1
Power of K: 0 = b6, b6 = 0
$$\pi_6 = \frac{L}{\tau}$$

7. $\pi_7 = t^{a7}\, T_i^{b7}\, \rho^{c7}\, \tau^{d7}\, T_o$
$\pi_7 = M^0 L^0 T^0 K^0 = [L]^{a7}[K]^{b7}[ML^{-3}]^{c7}[T]^{d7}[M^0 L^0 T^0 K^1]$
Power of M: 0 = c7, c7 = 0
Power of L: 0 = a7 – 3c7, a7 – 3(0) = 0, a7 = 0
Power of T: 0 = d7, d7 = 0
Power of K: 0 = b7 + 1, b7 = -1
$$\pi_7 = \frac{T_c}{T_i}$$

8. $\pi_8 = t^{a8}\, T_i^{b8}\, \rho^{c8}\, \tau^{d8}\, S$
$\pi_8 = M^0 L^0 T^0 K^0 = [L]^{a8}[K]^{b8}[ML^{-3}]^{c8}[T]^{d8}[M^1 L^{-1} T^{-2} K^0]$
Power of M: 0 = c8 + 1, c8 = -1
Power of L: 0 = a8 – 3c8 – 1, a8 – 3(-1) – 1 = 0, a8 = -2
Power of T: 0 = d8 – 2, d8 = 2
Power of K: 0 = b8, b8 = 0
$$\pi_8 = \frac{S\, \tau^2}{\rho\, t^2}$$

9. $\pi_9 = t^{a9}\, T_i^{b9}\, \rho^{c9}\, \tau^{d9}\, h_c$
$\pi_9 = M^0 L^0 T^0 K^0 = [L]^{a9}[K]^{b9}[ML^{-3}]^{c9}[T]^{d9}[M^1 L^0 T^{-3} K^{-1}]$
Power of M: 0 = c9 + 1, c9 = -1
Power of L: 0 = a9 – 3c9, a9 – 3(-1) = 0, a9 = -3
Power of T: 0 = d9 – 3, d9 = 3
Power of K: 0 = b9 – 1, b9 = 1
$$\pi_9 = \frac{T_I\, h_o\, \tau^3}{\rho\, t^3}$$

10. $\pi_{10} = t^{a10}\, T_i^{b10}\, \rho^{c10}\, \tau^{d10}\, V$
$\pi_{10} = M^0 L^0 T^0 K^0 = [L]^{a10}[K]^{b10}[ML^{-3}]^{c10}[T]^{d10}[M^0 L^3 T^0 K^0]$
Power of M: 0 = c10, c10 = 0
Power of L: 0 = a10 – 3c10 + 3, a10 – 3(0) +3 = 0, a10 = -3
Power of T: 0 = d10, d10 = 0
Power of K: 0 = b10, b10 = 0
$$\pi_{10} = \frac{V}{t^3}$$

Now, it is possible to write functional relationship as following.
$$F(\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7, \pi_8, \pi_9, \pi_{10}) = 0$$
$$f\left(\frac{T_I\, k\, \tau^3}{\rho\, t^4}, \frac{T_I\, h_I\, \tau^3}{\rho\, t^3}, \frac{T_I\, \alpha}{t}, \frac{E\, \tau^2}{\rho\, t^2}, \frac{T_I\, C\, \tau^2}{\rho\, t^5}, \frac{L}{\tau}, \frac{T_o}{T_I}, \frac{S\, \tau^2}{\rho\, t^2}, \frac{T_I\, h_o\, \tau^3}{\rho\, t^3}, \frac{V}{t^3}\right) = 0$$
$$L = \tau\, \varphi\left(\frac{T_I\, k\, \tau^3}{\rho\, t^4}, \frac{T_I\, h_I\, \tau^3}{\rho\, t^3}, \frac{T_I\, \alpha}{t}, \frac{E\, \tau^2}{\rho\, t^2}, \frac{T_I\, C\, \tau^2}{\rho\, t^5}, \frac{T_o}{T_I}, \frac{S\, \tau^2}{\rho\, t^2}, \frac{T_I\, h_o\, \tau^3}{\rho\, t^3}, \frac{V}{t^3}\right)$$

From experimental results and rational analysis, the empirical correlation is derived here to find out thermal fatigue life cycle of induction melting furnace refractory wall.
$$L = K \frac{h_o\, S}{h_i\, E} \left(\frac{\rho t^3}{\alpha T_i T_o\, V \tau^2}\right)^{1.5} \left(\frac{\rho t^2}{E \tau^2}\right)^{1.7}$$

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Table 1 Comparison of Numerical results with Empirical Correlation

Materials	Silica	Alumina	Magnesia	Zirconia	Unit
Internal Film Co-efficient hi	200	200	200	200	W/m^2 K
External Film Co-efficient ho	40	40	40	40	W/m^2 K
Thickness of wall	0.12	0.12	0.12	0.12	m
Volume	3000	3000	3000	3000	m^3
Density	2800	3400	3300	5000	Kg/m^3
Time Interval Δt	10	10	10	10	Seconds
Thermal Conductivity k	1.7	2.6	4	1.2	W/m K
Temperature outside Furnace Wall	303	303	303	303	Kelvin
Temperature inside Furnace Wall	1673	1873	1773	1873	Kelvin
Specific Heat	950	920	880	780	J/kg K
Elasticity Constant	0.19	0.232	0.19	0.26	N/m^2
Thermal Expansion Co-efficient	0.00000139	0.00000098	0.00000153	0.00000097	m/K
Ultimate Stress	500	500	600	600	Mpa
Answer of Equation	0.000207105	0.000320594	0.000333716	0.000982126	NA
Constant	1080000	1080000	1080000	1080000	NA
Empirical Correlation Answer	223.673555	346.2413801	360.413173	1060.696335	Cycles
Computer Program Results	233	347	358	1138	Cycles
% Error	-4%	-0.2%	0.006%	-6.7%	

Comparison of numerical results with developed empirical correlation is given in Table 1. This Empirical Correlation will be known as Shukla-Mehta's Correlation and Constant will be known as Shukla-Mehta's Constant which is having value 1080000. Shukla-Mehta's Correlation can predict the life cycle of induction furnace wall for diverse refractory materials.

Percentage of Error in the results of Shukla-Mehta's Correlation for silica ramming mass is -4 %, for alumina ramming mass is -0.2 %, for magnesia ramming mass is 0.06 % and for zirconia -6.7 %. Shukla-Mehta's Correlation can predict life cycle of any refractory material with + or – 10 % error with compare to numerical results. Because of many miscellaneous factors involved in thermal fatigue life cycle prediction of induction furnace wall, this limit can be considered acceptable. If zirconia is neglected as special refractory and not used practically then prediction error can be + or – 5 % only.

IV. CONCLUSION

An empirical correlation is invented by dimensional analysis and rational analysis which is proficient of directly prediction life cycle of the induction furnace wall for any refractory material and any capacity of furnace. Several dimensionless numbers are established using different quantities which are considered as significance parameters of life cycle for induction furnace wall. Then rational analysis is done for finding out precise correlation using investigational figures available from industries. This results in a very advanced investigation work as it will open up pioneering entryways for thermal fatigue life prediction arena.

This empirical correlation can be even modified and tailored to solve many miscellaneous thermal fatigue life problems in the field of mechanical engineering. Life cycle can also be found out with diverse probability to justify the miscellaneous behavior. Empirical correlation established is extremely valuable because with the use of its life cycle can be effortlessly and accurately predicted by simple data of material properties and geometrical features. This research will be supportive in solving countless complex thermal fatigue problems worldwide.

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