December 2009 Volume 5 Issue 4

Materials Science

Trade Science Inc.

An Indian Journal

Full Paper

MSAIJ, 5(4), 2009 [405-409]

Prediction of the thermal shock resistance of basic refractory materials using fracture resistance parameters

M.R.Izadpanah*

International Center of Science, High Technology & Environmental Sciences Mahan, Kerman, (IRAN)

E-mail : mizadpanah@yahoo.com

Received: 12th October, 2009 ; Accepted: 22nd October, 2009

ABSTRACT

Refractory materials are used in different industries. Knowledge of different properties of these materials is vital to the consumers and therefore the manufacturers hav to provide these properties. Among these thermal shock resistance is an essential property and is measured in terms of the number of cycles that a refractory material can withstand when subjected to standard conditions. This property is measured experimentally by varying the temperature in a known environment then the number of cycles the material withstands this treatment without spalling is a measure of its thermal shock resistance. Although this method of experimentation exists, but it is both expensive and time consuming. Various studies have been presented to predict this vital property, however, the range of applications are limited. The present study employs a test rig by which temperature distributions in magnesite samples are accurately measured. This information plus other results obtained from relevant tests on related properties are used to develop a model which predicts the number of quench cycles withstand by different samples when subjected to sudden temperature changes. The comparison of the theoretical values using the solution of the presented model with experimental data for different materials having different properties shows a close agreement.

KEYWORDS

Refractory materials;
Thermal shock resistance;
Temperature distribution.

INTRODUCTION

Refractory materials have various applications in those industries that use high temperatures in their production processes. Steel industry, in particular, is one of the major consumers of these materials.

High temperature application of these materials is accompanied by rapid temperature changes and associated thermal stresses which lead to the failure of these materials in service. The thermal shock resistance of refractories is determined using standard quench tests in which the material is heated and cooled subsequently and the number of quench cycles that a material can withstand prior to failure is taken as its resistance to thermal shock. However the experimental method of evaluation of this property is both time consuming and expensive. Hence the presentation of a model which could predict this property using other properties that are easier and less expensive to perform is very beneficial to both the producers and the consumers of refractories.

Several research works have been carried out to study thermal shock behavior of ceramics[1-4]. A limited number of attempts have been made to model thermal shock resistance of refractories[5]. Therefore, in applications where there is a need for assessing thermal shock performance of refractory materials references are scarce.

The present work studies systematically the temperature distribution and the resulted stresses in samples made of magnesite and upon analyzing the results a comprehensive model is presented which could predict the thermal stability of refractory materials.

EXPERIMENTAL

Experiments are carried out using the test rig shown in Figure 1. The test rig consists of a sample holding TABLE which is designed so that the heat transfer due to conduction reduces to minimum.

Stainless steel sheathed K type insulated junction thermocouples 0.5mm in diameter, 150mm in length are used to measure the surface and the centre temperatures. These thermocouples can measure temperatures ranging from 0 to 1100°C.

A data acquisition system, which consists of two boards, namely the CIO-DAS08 and the CIO-EXP32 cards that are connected to a desktop computer, is used to collect the data. The CIO-DAS08 card turns the PC into a medium speed data acquisition and control station suitable for data collection. A menu driven computer codes is used to process the acquired raw data. The processed data are then saved in a file for each test.

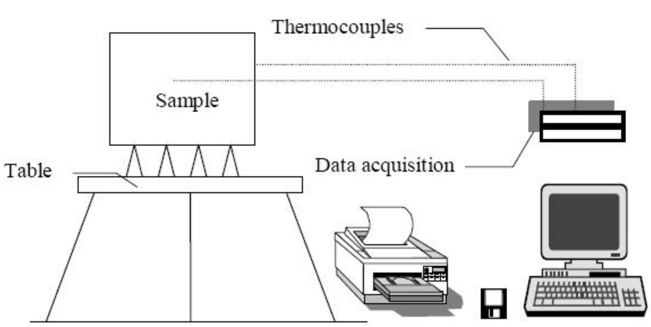

Figure 1 : Schematic diagram of the test rig

Experimental samples

Refractory materials used in this investigation are magnesite with different chemical compositions. The samples are dimensioned as 6×6×6 cm and supplied by Pars Refractories Company; a leading refractory manufacturer in Iran. The composition of these samples is given in TABLE 1.

TABLE 1 : Chemical, thermal and mechanical properties of samples

Properties			Samples				
			70DL	70DR	70 S	80 S	80 D
Chemical composition	Min.	MgO(%)	60	70	67.5	75	76
	Min.	Cr_2O_3(%)	16-18	10	10	8	8
	-	Al_2O_3(%)	13-15	-	-	-	-
	-	Fe_2O_3(%)	6-8	-	-	-	-
	-	CaO(%)	0.5-1	-	-	-	-
	Max	SiO_2(%)	2	2.5	3.5	3	2
Density(g/cm^3)			3.00	2.95	2.96	2.95	3.00
Thermal conductivity(W/mK)			2.53	2.45	2.47	2.43	2.32
Thermal Expansion(%)			1.00	1.10	0.90	1.25	1.25
Compressive strength(Mpa)			66	57	60	45	40
Young Modulus(Gpa)			16	18	17	20	23
Thermal shock resistance(cycles)			60	30	35	22	20
Biot number(-)			3.24	3.31	3.28	3.33	3.49
Fourier number(-)			23E-5	21E-5	23E-5	22E-5	20E-5

Experimental procedure

Samples are heated up in an electric furnace to 950°C. The samples are then quenched in still air while placed on the TABLE. The above procedure is repeated until failure occurs. The number of cycles that are withstood by the samples is taken as a measure of thermal shock resistance of the samples. The results are presented in TABLE 1. While samples are being cooled, thermocouples measure the temperatures at the surface and centre of the samples. Other relevant properties are evaluated according to standard tests methods. These tests are carried out at Pars Refractories Company's laboratories. The results for different samples are given in TABLE 1.

RESULTS AND DISCUSSIONS

The measurements of temperature at the surface and the centre as a function of time for 70 DL are presented in Figure 2. As it can be seen there is a signifi-

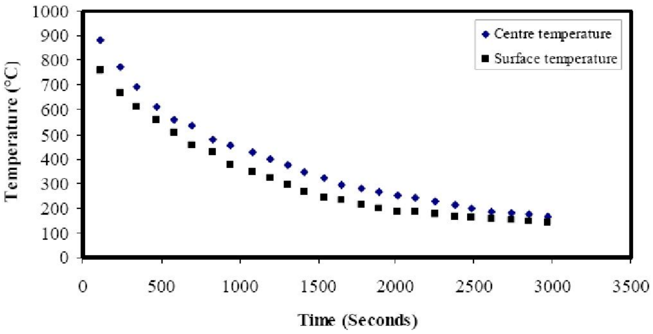

Figure 2 : Variations of temperature with time for sample 70 DL

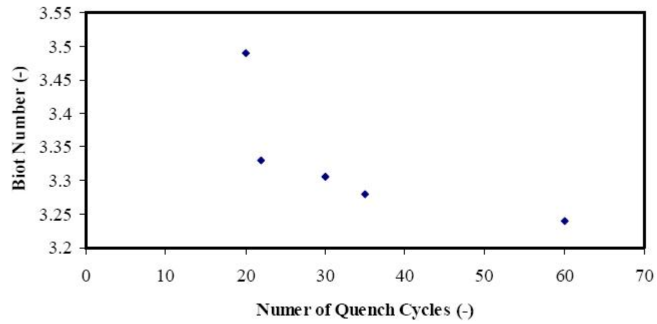

Figure 3 : Variations of biot number with number of quench cycles

cant difference between the two temperature profiles at different time intervals. This is due to the low thermal conductivity and also high values of Biot number which results in sample failure.

Figure 3, shows the variations of Biot number as a function of the number of quench cycles. This graph reveals the fact that a large number of quench cycles is associated with the samples whose Biot number are small. This suggests that for samples with small Biot number there exists a more uniform temperature distribution which justifies the higher number of quench cycles and hence developing less thermal stresses.

Formulation of model

Taking into consideration the importance of temperature distribution and its role in developing thermal stresses within the material, one can infer the significance of temperature distribution in predicting thermal shock resistance of refractory materials.

The modelling procedure starts with simplification of the energy equation. The unsteady state energy equation in a cubical sample in two dimensions assuming homogeneous properties yields[8]:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = \frac{1}{A}\frac{\partial T}{\partial t} \quad (1)$$

Attempts were made to use Heisler charts to solve the governing energy equation but due to low values of Fourier numbers, this procedure could not be employed[8]. Therefore the energy equation was solved numerically[6,8].

The finite difference method was employed to solve numerically the above partial differential equation. The equation was discretized using; central difference for the first and second terms on the left hand side and also the term on the right hand side. The algebraic equations are solved using Gauss-Seidel iteration technique.

The overall heat transfer coefficient which is used for the boundary nodes is;

$$\mathbf{h = h_{conv.} + h_{rad.}} \quad (2)$$

Where heat lost through convection mechanism is given by[8]:

$$\mathbf{h_{conv.} = 0.52(Gr \cdot Pr)^{0.25}\left(k/l\right)} \quad (3)$$

And the amount of heat lost through radiation is[8]:

$$\mathbf{h_{rad.} = \varepsilon \cdot \sigma \cdot \left(T_1^2 + T_2^2\right)\left(T_1 + T_2\right)} \quad (4)$$

To find the stress distribution, numerical solution of the temperature distribution is substituted in the following equation[9].

$$\mathbf{S = \alpha \cdot E \cdot \Delta T} \quad (5)$$

Figure 4, represents the theoretical temperature distribution for two different samples. Figure 5, illustrates the temperature distribution at different time intervals. Figure 6, compares the theoretical stress distribution at the surface and the centre of two different samples. These graphs emphasize the fact the existence of non - uniform temperature distribution will result in thermal stresses which in turn causes the failure of the material.

Since thermal stability depends on different parameters namely; thermal conductivity, strength, thermal expansion, Young modulus, etc. Therefore the property can be specified by the fracture resistance parameter given as[10];

$$\mathbf{R = \frac{S_M(1-\nu)}{\alpha \cdot E}} \quad (6)$$

Fracture resistance parameter could be used as a criterion to correlate thermal shock behaviour of refractory materials in terms of number of quench cycles. Hence the following correlation is suggested to predict the number of quench cycles, Ω, in terms of resistance

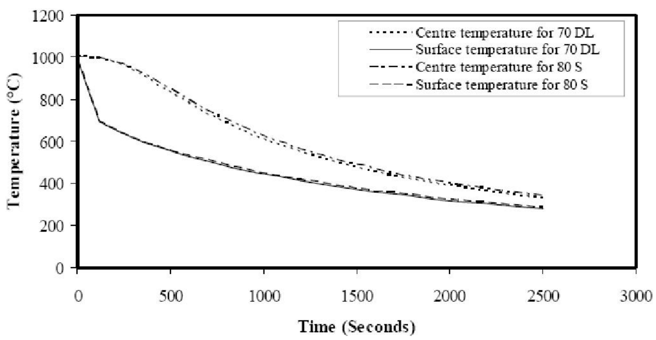

Figure 4 : Variations of theoretical temperature with time

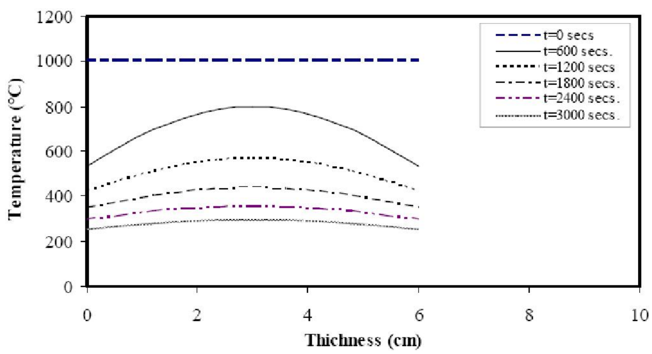

Figure 5 : Theoretical temperature distribution at different time intervals

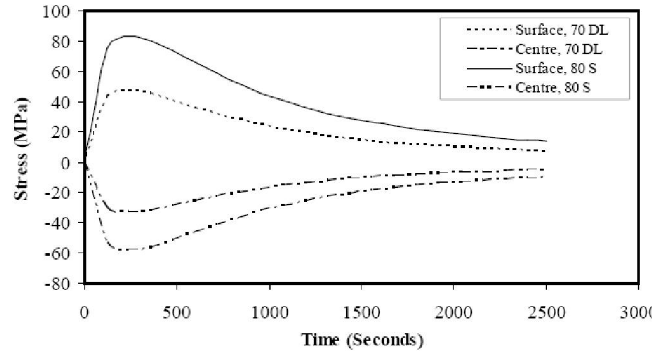

Figure 6 : Theoretical stress distribution for samples 70 DL and 80 S

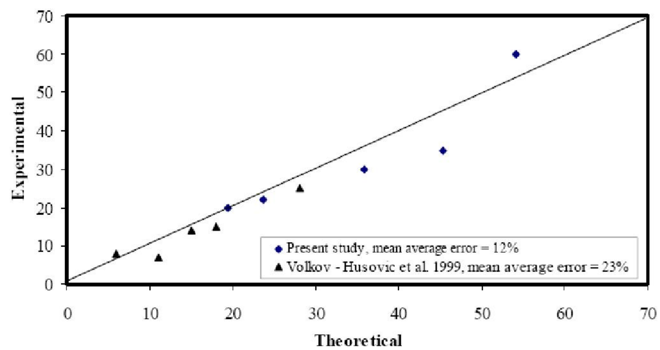

Figure 7 : Comparison of theoretical number of quench values with experimental data

parameter, R, for different materials used in the present investigation.

$$\Omega = a + b \cdot \Re^{c} \tag{7}$$

Where a, b and c are constants and their values determined using experimental data and $\Re$ is given by;

$$\Re = R/_{Bi} \tag{8}$$

The values of constants in equation (7) are calculated using non-linear regression. Therefore equation (7) becomes;

$$\Omega = 12 + 0.05\Re^{1.5} \tag{9}$$

Figure 7, represents the comparison of the theoretical values using equation (9) with experimental data. The comparison suggests a good agreement between the experimental data and the predicted values. A comparison of the results published by other researchers, as indicated in Figure 8, suggests that the presented model can be used to predict the thermal stability of other refractory materials.

CONCLUSIONS

Thermal stability of refractory materials is very important in manufacturing and using these materials. The experimental evaluation of this property is both time consuming and requires a high capital investment. To overcome these major drawbacks a mathematical model can be devised so that the thermal stability of refractories can be predicted with a suitable accuracy.

The present work presents a correlation for predicting the number of quench cycles in terms of other available properties of refractory materials. A comparison of the values obtained using the suggested correlation show that it can predict the experimental data obtained by the present authors as well as other researchers with a good accuracy.

NOMENCLATURE

A	Thermal Diffusivity, m^2/s
E	Young Modulus, GPa
h	Heat Transfer Coefficient, W/m^2 K
k	Thermal Conductivity, W/m K
l	Length, m
S	Stress, MPa
S_M	Strength, MPa
T	Temperature, °C
t	Time, sec.

	Greek Symbols
Ω	Number of Quench Cycles, -
α	Thermal Expansion Coefficient, -
ε	Emissivity, -
ν	Poisson Coefficient, -
ρ	Density, kg/m^3
σ	Stefan – Boltzman Constant, $W/m^2\ K^4$
	Dimensionless Groups
Bi	Biot Number
Gr	Grashof Number
Pr	Prandtl Number
	Subscripts
conv.	Convection
rad.	Radiation

REFERENCES

[1] D.P.H.Hasselman; J.Am.Ceram.Soc., **52**, 600 **(1969)**.
[2] D.P.H.Hasselman; J.Am.Ceram.Soc., **46**, 535 **(1963)**.
[3] J.Nakayama; J.Am.Ceram.Soc., **48**, 583 **(1965)**.
[4] J.Nakayama, M.Ishizuka; Am.Ceram.Soc.Bull., **45**, 666 **(1965)**.
[5] T.Volkov-Husovic, R.M.Jancic, M.Cvetkovic, D.Mitrakovic, Z.Popovic; Material Letters, **38**, 372 **(1999)**.
[6] G.M.Dusinberre; Heat Transfer Calculations by Finite Differences, International Textbook Company, Scranton, PA, **(1961)**.
[7] W.D.Kingery; J.Am.Ceram.Soc., **38,** 345 **(1955)**.
[8] J.P.Holman; Heat Transfer, McGraw-Hill Book Company, London, **(1989)**.
[9] D.P.H.Hasselman, J.R.Thomas Jr., M.P.Kamat, K.Satamurthy; J.Am.Ceram.Soc., **63**, 21 **(1980)**.
[10] K.Shaw; Refractories and Their Uses, Applied Science Publishers Ltd. London, **(1972)**.