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Prediction of the thermal shock resistance of refractory materials using *R* values

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Knowledge of the thermal shock resistance of refractory materials is of particular importance in a variety of applications. To meet the needs of these various applications, a number of thermal shock parameters based on material properties have been developed. The area of thermal shock resistance of refractories is often one of conflicting results in terms of agreement between experimental observations and predictions based on parameters of materials. The current study presents the temperature and stress distributions in magnesite samples. This information plus other results obtained from thermal and mechanical properties of these materials are used to develop a model which predicts the number of quench cycles for various refractory materials. The comparison of the theoretical values using the solution of the presented model with experimental data for materials having different thermal resistances shows a close agreement.

Key words: *thermal shock resistance; refractory material; modelling*

1. Introduction

Refractory materials have various applications in many industries such as cement, iron and steel, non-ferrous, ceramic, glass and power generation. Among other properties, which are very important in manufacturing and the consumer market, thermal shock resistance is still a challenge for refractory community. Thermal shock is the direct result of exposing the surface of refractory installations to rapid heating and cooling conditions which cause temperature gradients within the refractory blocks. Such gradients, in the case of uneven cooling or heating, may cause failure of the material [1, 2].

The thermal shock resistance of refractory materials is determined using standard quench tests [3, 4] 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

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resistance to thermal shock. However, the experimental method of evaluation of this property is both time consuming and expensive [1]. Hence, presentation of a model which could predict this property using other properties, being easier and less expensive to perform would be valuable.

Several research works have been carried out to study thermal shock behaviour of ceramics [5–8]. A limited number of attempts have been made to model thermal shock resistance of refractories [9, 10]. Therefore, information regarding the assessment of thermal stability of refractory materials is scarce.

In the present work, the temperature distribution and the resulted stresses in samples made of magnesite have been studied. Upon analyzing the results, a comprehensive model capable of predicting the thermal stability of refractory materials has been presented.

2. Experimental setup and procedure

Experimental set up. Experiments were carried out using the test rig shown in Fig. 1. The test rig consists of a sample holding table which is designed so that the heat transfer due to conduction is reduced to its minimum value. Stainless steel sheathed K type insulated junction thermocouples, 0.5 mm in diameter, 150 mm long were used to measure the surface and the centre temperatures. These thermocouples can measure temperatures ranging from 0 to 1100 °C.

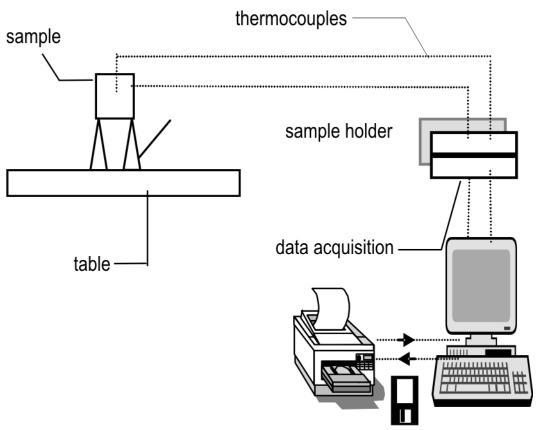

Fig. 1. Schematic diagram of the test rig

A data acquisition system consisting 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 code is used to process the acquired raw data. The processed data are then saved in a file for each test.

Samples. Refractory materials used in this investigation are magnesite with different chemical compositions. The samples of the size 6×6×6 cm^3 were supplied by the Pars Refractories Company, a leading refractory manufacturer in Iran. The chemical compositions of these samples are given in Table 1. Acronyms describing the samples will be used further in the paper.

Table 1. Chemical composition of the samples [wt. %]

Component	Sample				
	70DL	70DR	70S	80S	80D
MgO (min.)	60	70	67.5	75	76
Cr_2O_3 (min.)	16–18	10	10	8	8
Al_2O_3	13–15	–	–	–	–
Fe_2O_3	6–8	–	–	–	–
CaO	0.5–1	–	–	–	–
SiO_2 (max.)	2	2.5	3.5	3	2

Procedure. The samples were heated in an electric furnace to 950 °C and then quenched in still air while placed on the table. The above procedure was repeated until failure occurred. The number of cycles withstood by a sample is taken as a measure of its thermal shock resistance. The results are presented in Table 2. While the samples are cooled, the thermocouples measure the temperatures at the surface and in the centre of the samples. Other relevant parameters are given in Table 3. These have been evaluated according to standard test methods [3, 4]. The tests were carried out at laboratories of Pars Refractories Company.

Table 2. Number of quench cycles

Sample	70DL	70DR	70S	80S	80D
Number of cycles	41	30	35	22	20

Table 3. Thermal and mechanical properties of the samples

Parameter	Sample				
	70 DL	70 DR	70 S	80 S	80 D
Density [g /cm^3]	3.00	2.95	2.96	2.95	3.00
Thermal conductivity [W/(m·K)]	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
Heat capacity, c [J/kgK]	1	0.922	0.907	0.968	0.97
Poisson ratio, ν	0.2	0.2	0.2	0.2	0.2
Young modulus [GPa]	16	18	17	20	23
Biot number	3.24	3.31	3.28	3.33	3.49
Fourier number	23×10^{-5}	21×10^{-5}	23×10^{-5}	22×10^{-5}	20×10^{-5}

3. Formulation of the model

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

The modelling procedure starts with a simplification of the volume averaged energy equation. The unsteady state energy equation in a cubical sample in three dimensions assuming homogeneous properties yields [11]:

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}=\frac{1}{\kappa}\frac{\partial T}{\partial t} \tag{1}$$

The initial and boundary conditions applicable to the solution of the above partial differential equation with respect to the test bed under consideration are as follows:

$$T(x,y,z,0)=T_0 \tag{2}$$

$$\frac{\partial T(0,y,z,t)}{\partial x}=0 \tag{3}$$

$$\frac{\partial T(L,y,z,t)}{\partial x}=\frac{h}{k}\left(T(L,y,z,t)-T_\infty\right) \tag{4}$$

$$\frac{\partial T(x,0,z,t)}{\partial y}=0 \tag{5}$$

$$\frac{\partial T(x,L,z,t)}{\partial y}=\frac{h}{k}\left(T(x,L,z,t)-T_\infty\right) \tag{6}$$

$$\frac{\partial T(x,y,0,t)}{\partial z}=0 \tag{7}$$

$$\frac{\partial T(x,y,L,t)}{\partial z}=\frac{h}{k}\left(T(x,y,L,t)-T_\infty\right) \tag{8}$$

The overall heat transfer coefficient h used in the boundary conditions is given by

$$h=h_{\mathrm{conv}}+h_{\mathrm{rad}} \tag{9}$$

where heat lost through convection is given by [11]

$$h_{\mathrm{conv}}=0.52\left(Gr\,Pr\right)^{0.25}\left(\frac{k}{l}\right) \tag{10}$$

In the above equations, T stands for temperature, t is time, κ is the thermal diffusivity, k – thermal conductivity, L – the sample length, and Gr and Pr stand for the Grashof and Prandtl numbers, respectively.

The amount of heat lost through radiation is [11]:

$$h_{\text{rad}} = \varepsilon\sigma\left(T_1^2 + T_2^2\right)\left(T_1 + T_2\right) \tag{11}$$

where ε and σ are the emissivity and Stefan–Boltzman constant, respectively.

The analytical solution of Eq. (1) yields the following general solution for the temperature distribution in the test piece.

$$\begin{aligned} T(x,y,z,t) = T_0 + 8(T_0 - T_\infty)\sum_{n=1}^{\infty}\sum_{m=1}^{\infty}\sum_{p=1}^{\infty} & \frac{\sin(\lambda_n L)\cos(\lambda_n x)}{\lambda_n L + \sin(\lambda_n L)\cos(\lambda_n L)} \\ & \times\frac{\sin(\beta_m L)\cos(\beta_m y)}{\beta_m L + \sin(\beta_m L)\cos(\beta_m l)} \\ & \times\frac{\sin(\gamma_p L)\cos(\gamma_p z)}{\gamma_p L + \sin(\gamma_p L)\cos(\gamma_p L)} \mathrm{e}^{\left(-\kappa t\left(\lambda_n^2+\beta_m^2+\gamma_p^2\right)\right)} \end{aligned} \tag{12}$$

To find the stress S distribution, the above solution of the temperature distribution is substituted in the following equation [9]:

$$S(x,y,z,t) = \frac{\alpha E}{1-\nu}(T_m(x,y,z,t) - T(x,y,z,t)) \tag{13}$$

where

$$T_m(x,y,z,t) = \frac{1}{8L^3}\int_{-L}^{L}\int_{-L}^{L}\int_{-L}^{L} T(x,y,z,t)dxdydz \tag{14}$$

ν is the Poisson coefficient, and α is the thermal expansion coefficient. Equation (13) gives the stress distribution in the samples under the test conditions.

4. Results and discussion

A comparison of one and three dimensional temperature distributions at the centre and surface of the 70DL sample with experimental data is shown in Fig. 2. As suggested by the aforementioned figure, there is a considerable difference between the 1D distributions with the experimental data; and therefore it can be concluded that the one dimensional solution results in appreciable errors when analyzing the thermal behaviour of the samples. Hence, the analytical procedures are considered and solved using 3D forms.

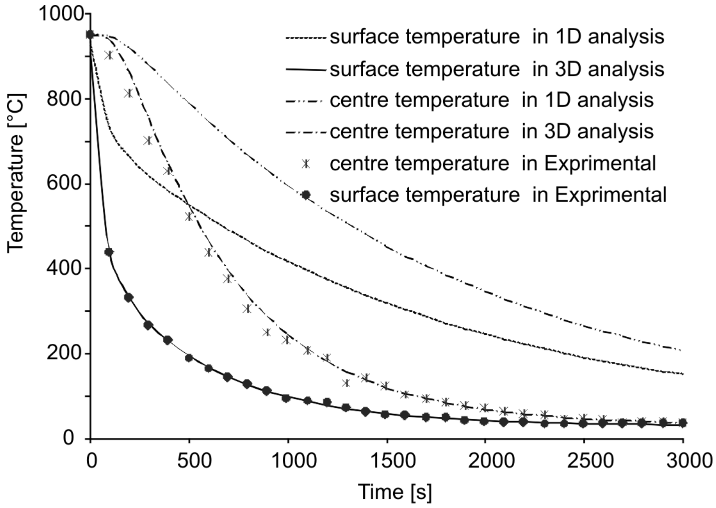

Fig. 2. Dependences of theoretical and experimental temperature distributions on time for 70DL sample

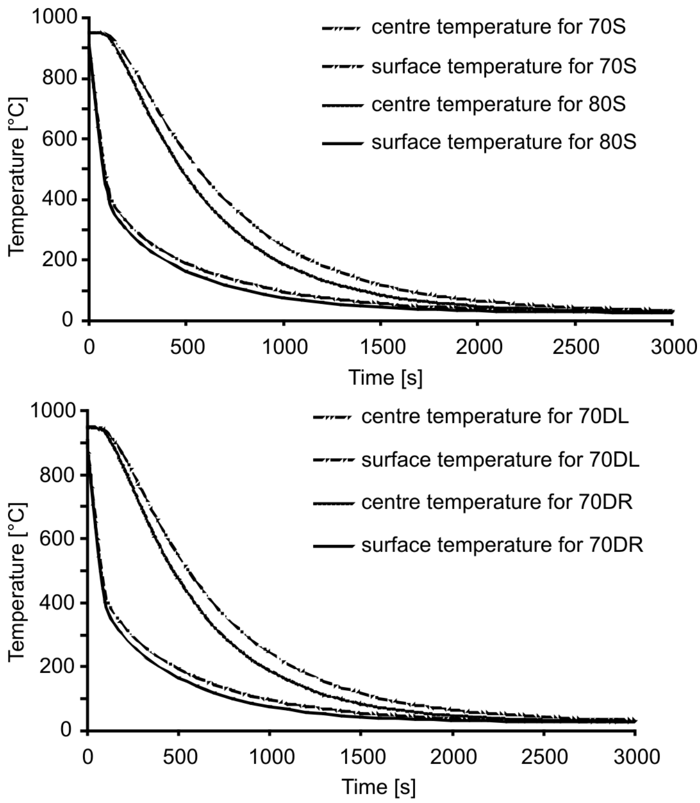

Fig. 3. Dependences of three dimensional temperature distributions on time for various samples subject to thermal shock in still air

Time dependences of temperatures at the surface and the centre for the 70 DL,70S and 80S samples are presented in Fig. 3. As can be seen, there is a significant difference between the two temperature profiles at different time intervals. This is due to the low thermal conductivity which is responsible for the existence of thermal stresses and hence sample failure [6].

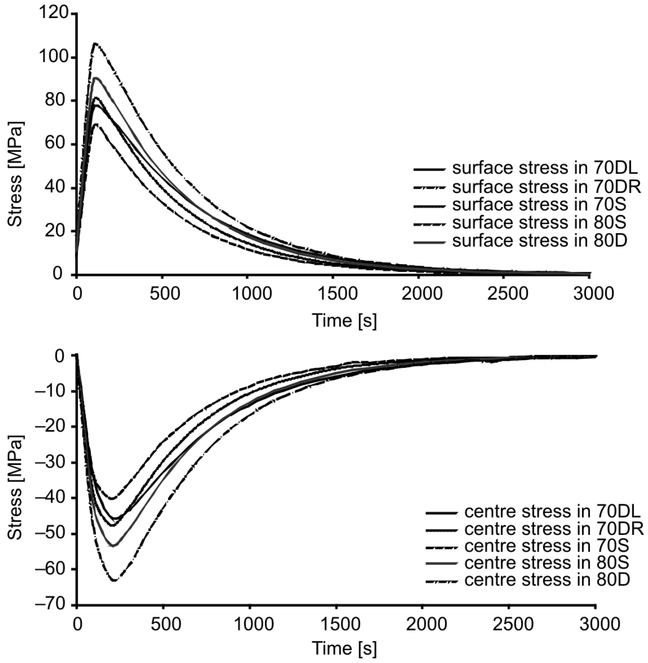

Fig. 4. Dependences of three dimensional stress distributions on time for various samples subject to thermal shock in still air

In Figure 4, the theoretical stress distributions at the surface and the centre of the samples are shown. These graphs emphasize the fact that the existence of a non-uniform temperature distribution will result in different stresses at the surface and the centre of the samples. Comparison of thermal shock behaviour of the samples can therefore be related to material thermal stability.

5. Modelling

Thermal stability of refractory materials is measured using standard laboratory tests. The ability of the material to withstand the thermal shock corresponds to the number of cycles that the material can stand the cooling–heating cycles before it fails.

It has long been the practice to use the fracture resistance parameter *R* to represent the thermal shock ability of these materials. *R* depends on various thermal and mechanical properties. However, the dependence of this parameter on the aforementioned properties only classifies them in order of their thermal resistance which is given by

$$R = \frac{S_M (1-\nu)}{\alpha E} \tag{15}$$

where S_M is the strength and E stands for the Young modulus.

The fracture resistance parameter, however, could be used as a criterion to correlate thermal shock behaviour of refractory materials in terms of the number of quench cycles. Considering the dependence of the number of quench cycles on various properties, the following correlation can be suggested in terms of resistance parameter R and the Biot number for various materials used in the present investigation.

$$\Omega = a + b \ln \Re \tag{16}$$

where Ω is the number of quench cycles, a and b are constants and their values are determined from experimental data, and $\Re$ is given by:

$$\Re = \frac{RkBi^{0.28}}{\kappa} \tag{17}$$

where Bi is the Biot number. The values of constants in Eq. (16) are calculated using non-linear regression. Therefore, Eq. (16) becomes:

$$\Omega = -113 + 22 \ln \Re \tag{18}$$

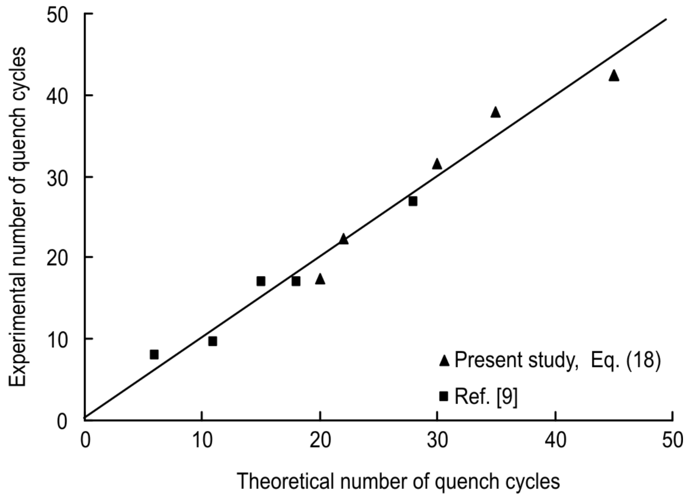

Fig. 5. Comparison of theoretical number of quench cycles with experimental data

Table 4. Results of non-linear regression

Comparison Ω with number of quench experiments	R^2
Present study	0.9837
Present study and [9]	0.9706
Ref. [9]	0.9616

Figure 5 represents the comparison of the theoretical values using Eq. (18) with experimental data. The comparison establishes an excellent agreement between the experimental data and the predicted values.

A comparison of the results published by Volkov–Husovic et. al. [9] as indicated in Fig. 5 and the R^2 values given in Table 4 suggests that the presented model can be used to predict the thermal stability of other refractory materials.

6. Conclusions

Based on the results and discussions presented in the current research it can be concluded that the thermal shock resistance of refractory materials is a very important feature of these materials, and its dependence on the temperature as well as stress distributions is of greatest significance.

Traditional use of R parameters only sorts this property in order of magnitude and cannot give a quantitative measure of thermal shock resistance of refractory materials. However, this factor can be correlated with the number of quench cycles so that thermal stability can be predicted with a suitable accuracy.

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

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