Heat Transfer Design Considerations for Refractory Linings, Part 1

G. Palmer

This paper discusses the problems associated when undertaking heat transfer analysis, specifically, the effect of taking simplified assumptions and the problem of large variations in refractory thermal conductivity values. The effect of refractory material conductivity values and air gaps at the interface in a 1D analysis is provided. It is shown that using a 1D heat transfer model to predict temperature profiles in refractory systems can result in serious errors.

1 Introduction

The heat transfer analysis of multi-layer refractory concretes in both transient and steady state conditions is particularly important for many pyro-processing industries. Knowing the temperature profile through the different layers is important for design and operational trouble-shooting. It is clear that the design of refractory linings is becoming increasingly important both structurally and in energy efficiency terms. Also industry “fitness for service” (FFS) guidelines for pressure vessels require that the plant is safe for personnel and the public. FFS assessments will include refractory linings and the practice of simply changing the refractory design without proper engineering approval could leave companies exposed.

Heat transfer theory is generally well understood and it is possible to predict temperature profiles under various conditions with reasonable accuracy, where accurate thermal property and convective / radiative boundary conditions are known. Refractory linings are generally composed of multiple layers of varying insulating materials and a dense abrasion resistant hot face layer. For steady conditions, when the layer is flat or thin (thickness < 5 % of the radius of curvature), conduction heat flow, Q, through each layer is well defined by

\[ Q = k / \Delta x \times A \Delta T \]

where \( k \) is the average thermal conductivity of the layer material, \( \Delta x \) its thickness, \( A \) the area for heat transfer and \( \Delta T \) the temperature difference across the layer. Convection is generally applied to one or both sides by using some simplified correlations to account for wind and other flow effects.

In many cases, simplifying assumptions are made when undertaking a heat transfer analysis. Incorrect assumptions can lead to poor or the wrong selection of materials which in turn can lead to excess heat loss, refractory failure, overheating of vessels, too low shell temperatures or poor lining design with increased capital costs. Earlier research [1, 2] has found that there is a significant difference between data-sheet thermal conductivity and published data [5, 9].

Early research [1, 2] has found that there is a significant difference between data-sheet thermal conductivity and published data. The effect of higher material thermal conductivity values and gaps between concrete layers are discussed.

This paper discusses the problems associated when undertaking heat transfer analysis, specifically, the effect of taking simplified assumptions and the problem of large variations in refractory thermal conductivity values. The effect of refractory material conductivity values and air gaps at the interface in a 1D analysis is provided. It is shown that using a 1D heat transfer model to predict temperature profiles in refractory systems can result in serious errors.

Greg Palmer
Palmer Technologies Pty. Ltd.
Coorparoo DC, Queensland, Australia

Tony Howes
School of Engineering
The University of Queensland
4072 St. Lucia, Australia

Corresponding author: Greg Palmer
E-mail: Greg.Palmer@palmertechgroup.com

Keywords: Heat transfer, refractory linings, design considerations

Received: 09.11.2009
Accepted: 11.11.2009

Fig. 1 Thermal conductivity of refractory versus density comparison from published data [5, 9]
2 Thermal conductivity measurement and estimation

Heat transfer analysis is one of the most commonly used tools in evaluating and designing refractory structures. The analysis is almost always carried out using a 1D steady state program assuming perfect conduction through composite layers. This requires the use of refractory thermal conductivity and the most commonly used source are manufacturer’s data sheets. Hence the accuracy of reported thermal conductivity data and the validity of perfect conduction through composite layers are particularly important for designers.

There are a number of methods for determining thermal conductivity of refractory materials, for example, the hot wire method, calorimetry and laser flash thermal diffusivity. The aim is not to discuss these techniques but rather to discuss variations on temperature predictions between reported and predicted thermal conductivity.

The most common method to determine refractory thermal conductivity has been the calorimetry method which as been used for more than 60 years. It would be safe to say that the hot-wire method is now more frequently used due to speed and cost. Thermal conductivity of refractory materials has been studied both theoretically [3, 4] and practically [1, 5, 6, 7]. This research has found that the hot-wire method is well suited for heterogeneous refractory materials but not well suited for non-isotropic materials like insulation fibreboard [8]. In 1988 Crowley and Young [1] studied a number of different thermal conductivity test techniques and concluded that there were significant differences between static and dynamic methods. It was also concluded that the determination of the thermal conductivity (k) using the comparative test1), which relates k to geometric bulk density2), was the most consistent and agreed closely with the hot-wire data. They also found that the thermal conductivity for materials of similar density and composition often had thermal conductivities that differed from the published data often by as much as 50%.

A more recent analysis undertaken by Akioishi et al [5] investigated the relationship of thermal conductivity with volumetric bulk density3), and temperature for alumina and fireclay refractories. The investigation used the hot-wire technique and the results were statistically analyzed using the least squares method. A correlation was developed for fireclay and alumina refractories with volumetric bulk density in the range of

---

1) Using known standard materials and comparing temperature differentials across the standards
2) Determined by sample measurement and weight
3) Immersion technique
4) P-Thermal is a 1D transient heat transfer program developed by the authors

---

Fig. 2 Comparison of data sheet thermal conductivity and predicted thermal conductivity of dense and insulation castables

Fig. 3 Thermovision of furnace roof showing shell temperatures
550 kg/m³ and 3140 kg/m³ with porosity in the range of 15 to 81 %.

The relation for \( k \) in a range of refractories is shown in equation 1. This equation was reported to be valid for materials for \( 25 \, ^\circ\text{C} \leq T \leq 1200 \, ^\circ\text{C}, 550 \, \text{kg/m}^3 \leq \rho_v \leq 3140 \, \text{kg/m}^3 \) and 36 mass-% \( \leq \text{Al}_2\text{O}_3 \leq 94 \) mass-%.

The work published by Crowley and Young [1] presents data suitable for comparison purposes. The field data published by Crowley and Young [9] was also compared against the Akiyoshi et al. [5] correlation and is plotted in Fig. 1. This shows an excellent correlation between refractory thermal conductivity measured by Crowley and Young and Akiyoshi et al.

Fig. 2 shows the difference between the manufacturer’s data sheet thermal conductivity values and predicted thermal conductivity using equation 1, for four different refractory castables. It can be seen there is a significant difference between predicted and datasheet thermal conductivity values, in some cases the error is greater than 50 %.

This is in line with data published by Crowley and Young [1]. Published literature has found that the hot-wire method is an accurate and reliable [10, 11] method for determining thermal conductivity of refractory material. Thus it is concluded that correlations based on the hot-wire test can be used to accurately predict refractory thermal conductivity. It is also concluded that manufacturer’s data sheet thermal conductivity values in some cases can be very inaccurate for unknown reasons.

3 Analysis for a one layer system

An example for a furnace roof is used to show the difference between thermal conductivity values under perfect conduction for a one refractory layer system. The shell temperature was compared to a 1D P-Thermal [12] heat transfer model using manufacturer’s data sheet thermal conductivity and the refractory thermal conductivity predicted by equation 1 for a single insulation layer.

Fig. 3 shows an infrared image of a furnace roof with 150 mm thick insulation refractory under a 6 mm carbon steel shell. The temperatures were taken shortly after start up and the refractory lining had been completely replaced. The shell temperature varies from 149 °C (133 °C near the edge) to 160 °C.

The 1D heat transfer model using the predicted thermal conductivity data (equation 1) is shown in Fig. 4. The 1D model for the one layer system is 156 °C which validates the refractory thermal conductivity values predicted by equation 1 (correlated to the hot-wire method).

The 1D heat transfer model using the manufacturer’s data sheet thermal conductivity predicts a steady state shell temperature of 121 °C. This is significantly less than what has been measured from actual field data. It is concluded that a 1D heat transfer model using the manufacturer’s data sheet thermal conductivity is likely to under-predict temperature profiles in refractories systems by 20 to 30 %. If the refractory thermal conductivity values measured by the hot-wire technique or calculated by equation 1 is used in a 1D perfect model then the shell temperature can be predicted to within 5 % for a one layer system. It is concluded that correlations based on the hot-wire test can be

\[
k = \exp\left(\frac{-2.892 + 1.543 \times 10^{-3} T - 4.908 \times 10^{-7} T^2}{1555 - 9.277 \times 10^{-4} T + 4.095 \times 10^{-7} T^2}\right) \rho_v \tag{1}
\]
used to accurately predict refractory thermal conductivity in a one layer refractory system using a 1D heat transfer model.

4 Analysis for a two layer system with and without air gaps

Due to the fact that small air gaps exist between refractory composite layers a 1D model was developed which included an air gap at the interface between the two concrete layers in order to study the effect of data-sheet thermal conductivity on lining temperature profiles.

Previous research has shown that two refractory conditions are existing, the first is the green state when the concrete is first cast [13]. In this condition the bonding between the two concrete layers is most likely to be well bonded. The second and most important condition for designers is the fired state when the concrete has dried and gaps can exist at the interface.

The heat transfer for a two layer system (shell, insulation and hot-face) was evaluated by analyzing a reactor vessel. The original refractory lining is composed of 150 mm Kastolite 2300LI and 100 mm 1800 grade hot-face. The reactor operates at a temperature of 1250 °C.

Fig. 5 shows the shell temperatures for a reactor which had a hotspot in one area. The shell temperature away from the hotspot was approximately 180 °C. After the hotspot was repaired the shell temperature was monitored using welded thermocouple wire. The temperature varied from 160 °C to 180 °C. The temperature profile was calculated using a 1D heat transfer model (without an air gap) using both Akiyoshi (eqn 1) and manufacturer’s data sheet k values. The temperature profile using k calculated from equation 1 is shown in Fig. 6. This predicts a shell temperature of 209 °C.

Repeating the analysis using the manufacturer’s data sheet k values has a temperature profile as shown in Fig. 7. This predicts a shell temperature of 195 °C which is higher than the measured shell temperature by approximately 15 °C.

The analysis is repeated again using the Akiyoshi k values (equation 1) with an air gap. The temperature profile with air gap of ~10 W/m²K at the interface is shown in Fig. 8. In this case the predicted shell temperature is 181 °C which is within the measured shell temperature range.
It is concluded that the effect of a gap in the order 1 mm at the interface between the concrete layers is important and should be taken into consideration when designing refractory linings.

5 Conclusions
It is concluded that the current design procedure of using a 1D heat transfer model to predict temperature profiles in refractory systems can result in serious errors and the use of simplified forced convection coefficient equations can lead to errors of 25 % or more. The analysis and historical data shows that manufacturer’s published thermal conductivity values can be very inaccurate for unknown reasons. The error in the manufacturer’s thermal conductivity can be by as much as 50 %. Research by others has shown that correlations based on the hot-wire test can accurately predict refractory thermal conductivity. It has been found that using hot-wire thermal conductivity data with an interface air gap is an accurate method for predicting temperature profiles in refractory systems.

References