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The curing of powder coatings using gaseous infrared heaters: An analytical model to assess the process thermal efficiency

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Abstract — This experimental investigation is structured to determine the efficiency of energy transfer between a gaseous infrared burner and a powder coated surface being cured. The results from the experimental burner tests are interpreted using a Monte Carlo based numerical simulation. This simulation incorporates both an Edwards' exponential wide band model for the spectrally selective energy absorption and emission in the flue gas, and test measurements for the powders' spectral absorption characteristics. The results from the simulation show that efficiency of the energy transfer from the natural gas stream to the powdered surface ranges between 25 % and 30 %, when the burner is operating at stoichiometric conditions. The highest efficiency was obtained for the darkest coloured powder. The energy efficiency was also found to increase with burner temperature. However, the quality of the cured surface tended to decrease if the temperature rise was significant. © 2000 Éditions scientifiques et médicales Elsevier SAS

infrared radiation / curing / powder coating / process efficiency

Nomenclature

e	(hemispherical total) emissive power	$W{\cdot}m^{-2}$
Q	energy per unit time	W
T	absolute temperature	K
t	duration	s
α	(hemispherical total) absorptivity	
ε	(hemispherical total) emissivity	
η	wavenumber	m^{-1}
η	efficiency	

Subscripts

b	blackbody, burner
chem	chemical
ht	radiant heat transfer
net	net radiant heat transfer, net calorific value
P	process
p	powder coating
R	radiation
tot	total
η	spectral (wavenumber dependent)

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1. INTRODUCTION

Powder coating is a frequently used manufacturing procedure, employed to "paint" the surfaces of completed products. In the initial stage of this procedure electrostatically charged powder is sprayed on the "grounded" product surface. The surface is then heated in an oven or dryer until the powder particles melt, continued heating causes the molten layer to recrystallise. This vitreous layer forms a continuous thin protective film firmly bonded to the product when the surface cools. Typical values for the melt and recrystallisation temperatures for powders are 50 °C and 150 °C. Both the rate of heating and the maximum temperature to which the powder coating is heated have a strong influence on the quality of the cured product. Deviation from these optimum values can lead to coatings which are brittle or coatings which do not adhere to the product surface. The derivation of the optimal heating and cooling rates for the coated surface depends primarily on the previous experience of the plant operator. No analytical optimisation models of the curing process have yet been developed.

The powder curing process is normally conducted in a hot air convection oven, but infrared ovens are becoming more acceptable because of their enhanced speed of material processing and lower capital cost [1]. The high energy flow rates which develop within infrared ovens can also be used to ensure that the heating of the product is limited to a surface effect. The use of infrared ovens is however generally restricted to products which have a flat geometry [2], such as steel strip. The energy source in an infrared oven can be either an electric resistance element or a gas burner. Electrically heated infrared ovens tend to have much higher thermal efficiencies [3] because of their higher operating temperature of the heater and their inherently lower convective losses. Gas powered ovens [1, 4] do, however, have much lower operating costs and the relatively lower rates of heat transfer to the product are known to improve the quality of the cured surface.

The objective of the current study is to gain some understanding of the energy transfer which develops during the curing process within a gas fired infrared oven. In this type of oven, heat is supplied to the powder coating by thermal radiation emitted from both the gas burner surface and the flue gases. Determining the radiative properties of the burner and the powder coating was a key feature of the study. The experimental work supporting this investigation was performed in a small test oven which was fitted with one of three commercially available burner heads and a powder coated plate. Seven different compositions of powder were tested. These powders were formulated to produce one of four colours.

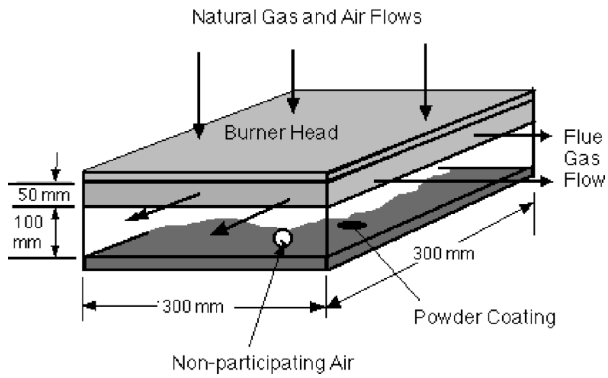


Figure 1. Test arrangement of the burner.

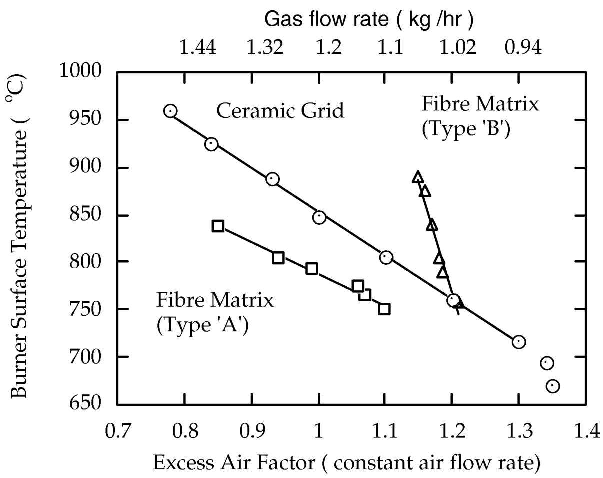


Figure 2. Change in the burner surface temperature with excess air factor.

2. RESULTS FROM THE BURNER TESTS

The arrangement of both the burner head and the powder coated surface in the test oven is shown in *figure 1*. The natural gas and air flows to the burner were accurately measured and controlled. During all of the tests the air flow rate to the burner head was kept constant. The adjustment of the mixing ratio control was the mechanism used to change the temperature of the burner. A significant limitation in this arrangement was the restriction which the natural gas supply pressure imposed on the mixture pressure, thus affecting the operating temperature range of the burner. Thermocouples imbedded in the outer surface of the burner were used to monitor its operating temperature. The composition of the natural gas was monitored daily and the average values used in the analysis of the process are: methane 84.63 %, ethane 7.21 %, propane 3.21 %, nitrogen 2.62 % and carbon dioxide 2.33 %. The average net calorific value of the gas was 36.19 $MJ \cdot kg^{-1}$.

Tests were conducted using three commercially available designs of porous radiant burner heads. Two of the heads were constructed from fibre matrix material, the third formed from a ceramic grid. The fibre matrix materials chosen had different thermal properties and the ceramic grid head was constructed with an array of 0.8 mm holes, on a 1.4 mm triangular pitch. The results from these tests are shown in *figure 2*, where the relationship between the reducing burner surface temperature and the increasing excess air (decreasing gas flow rate) is quantified. Observations and measurements made during the tests indicate that the combustion and surface temperatures were less uniform when the “type B” fibre matrix burner was tested. The frictional pressure drop in this head was high and this is believed to have effected its performance.

Most of the tests were conducted using the ceramic grid design since its fluid flow and pressure drop requirements more closely matched those available in the test facility. The test comparison with the more expensive fibre matrix heads has been included because they are frequently used in curing applications where a rapid response to product temperature is required.

In the subsequent analysis of the burner performance, the combustion process within the unit has been described using the molar equation for stoichiometric combustion:

$$1\,\text{natural gas} + 2.109\,O_2 + 7.934\,N_2 \Rightarrow 1.112\,CO_2 + 2.040\,H_2O + 7.960\,N_2 \quad (1)$$

Additional combustion products in the flue gas are assumed to be unburnt oxygen if the mixture is lean or unburnt hydrocarbons if the mixture is rich. Shielded thermocouples were used to measure the temperature distribution in the gas space beneath the burner. These measurements show that as the flue gas flows along the burner surface it forms a layer of almost constant thickness (50 mm at stoichiometric conditions) and that the temperature of this layer is similar to the burner temperature. The uniformity of these measurements suggests that the laterally flowing flue gas stream did not readily blend with the colder air beneath it and that its composition will not change. The air beneath the flue gas does not participate in the overall radiation energy transfer process, but the main radiation losses from the system are through the surfaces which surround this volume.

The tests were conducted by sliding a powder coated test sample under the burner, the thermal response of the powder was measured by thermocouples located under its surface. *Figure 3* shows the thermal history of a typical sample.

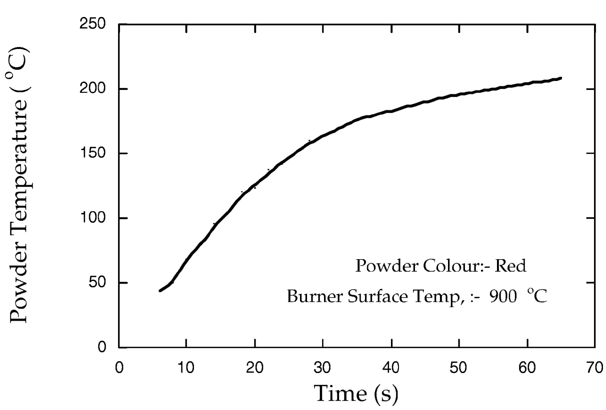


Figure 3. Increase in the powder temperature during the curing process.

3. PROCESS EFFICIENCY

The efficiency of the energy transfer between the combustion gas supply and the powder coated surface (η_{tot}) depends on both the effectiveness of the burner (η_R) and the thermal efficiency of the heat transferred from the burner through the oven to the powder (η_{ht}) [5], *viz.*,

$$\eta_{tot} = \eta_R \eta_{ht} \quad (2)$$

These component efficiencies can be further defined as follows.

- Burner effectiveness is a measure of the burner ability to convert the chemical energy of the gases being burnt (Q_{chem}) into radiant energy (Q_R):

$$\eta_R = \frac{Q_R}{Q_{chem}} \quad (3)$$

This efficiency is a characteristic feature for the burner which primarily depends on its design and location. The burners used in these tests are positioned horizontally and the gas is supplied from above. Radiant energy is emitted by both the burner surface and the flue gases. The thermal boundary of the burner is therefore considered to be the lower edge of the flue gas layer.

- The radiation heat transfer efficiency connects the net heat flux (Q_{net}) absorbed by the powder coating to the radiant energy (Q_R) emitted by the burner and flue gas:

$$\eta_{ht} = \frac{Q_{net}}{Q_R} \quad (4)$$

The efficiency of this energy transfer process depends on both the oven geometry and the spectral properties of the powder. The efficiency of this process will be higher in those regions where high spectral absorptivity of the powder coincides with high incident radiation.

4. ABSORPTIVITIES OF THE POWDERS

The seven powders used in the tests were similar to those used commercially in gas fired infrared ovens. The spectral absorptivity of the powder was calculated from tests which measured its reflectivity. The instrument used for these measurements was a Fourier-transform infrared spectrometer fitted with a diffuse reflectance accessory (DRIFTS). This accessory was based on a Harricks “Praying Mantis” design and was able to measure values in the wavenumber range between 400 cm^{-1} and 4 000 cm^{-1}, with a resolution of 2 cm^{-1}. The measured

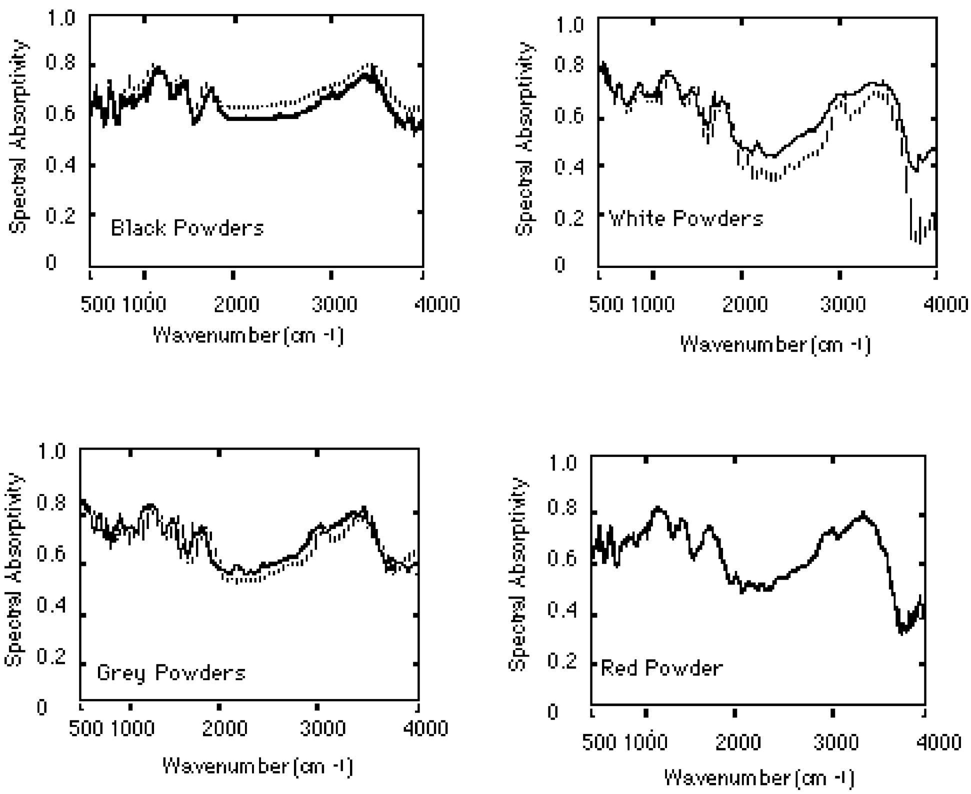


Figure 4. Absorptivity of powders, found by using a diffuse reflectance Fourier-transform infrared spectroscope.

values for spectral reflectivities were further checked using a photo-acoustic attachment, fitted to the same spectrometer.

Four colours of powder were tested and there were two different chemical compositions for each colour except red. The results produced in *figure 4* show that both powder colour and composition influences its spectral absorptivity. This influence is particularly notable for wavenumbers between 2 000 cm^{-1} and 3 000 cm^{-1} and for the region where the wavenumbers are greater than 3 500 cm^{-1}. Within both of these regions the darker powders (which also absorb more light in the visible range) absorb more infrared energy. This effect is due to the spectral characteristics of the powder component which defines its colour. In subsequent sections where the effects of colour are discussed, the samples used are those which in *figure 4* have solid lines.

5. ANALYTICAL MODEL

The main components of the analytical model are: the burner surface, the powder coated surface, the flue gas mixture, the nonparticipating air and the four vertical planes surrounding the nonparticipating air volume. All of these components are shown in *figure 1*. The model assumes that the thermodynamic and radiative properties for each of the component surfaces are uniform and constant. In addition, the burner and powder coating surfaces are assumed to be isothermal. The radiant energy flows between the elements were analysed in the model using a Monte Carlo algorithm [5, 6]. This solution method was selected because of the ease with which the spectral dependencies of the radiative properties could be included and because the model was to be used to calculate radiative heat transfer rates, rather than convective heat transfer rates. Convective heat transfer was not included in this analysis since the circulation patterns within the flue gas and nonparticipating air were unknown. The mass movement of these fluid streams will have a cooling effect on the burner surface, but the influence of this effect has been minimised by the use of test measurements to characterise the burner surface temperature.

The burner surface was modelled as a diffuse-grey body. The total emissivity for the ceramic grid burner was measured to be 0.90, the fibre matrix heads were found to have similar values. The spectral properties of the burner surfaces could not be assessed. However, Lampinen et al. [3] have shown that the emissivity of a similar gas fired ceramic burner was almost independent of wavenumber.

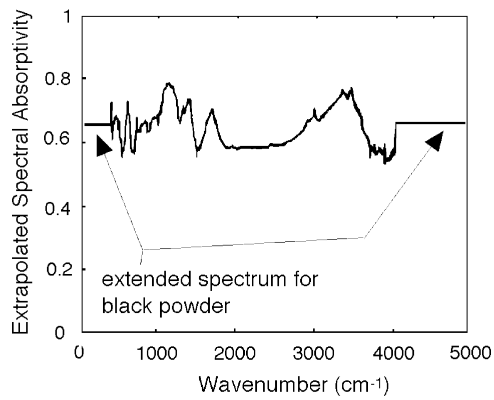
The powder coating surface was also modelled as a single isothermal element. Within this element the measured values of the powder's spectral absorption coefficient were extrapolated to encompass the complete wavenumber domain, $\eta \in [0, \infty]$. In this extrapolation it was assumed that the mean emissivity $\bar{\varepsilon}(T)$ of the powder in the measured range equalled its total emissivity $\varepsilon(T)$. This mean emissivity can be calculated for different powder temperatures from

$$\bar{\varepsilon}(T) = \frac{\int_{\eta_1}^{\eta_2} \alpha_\eta(\eta) e_{\eta,\mathrm{b}}(\eta, T)\,\mathrm{d}\eta}{\int_{\eta_1}^{\eta_2} e_{\eta,\mathrm{b}}(\eta, T)\,\mathrm{d}\eta} \qquad (5)$$

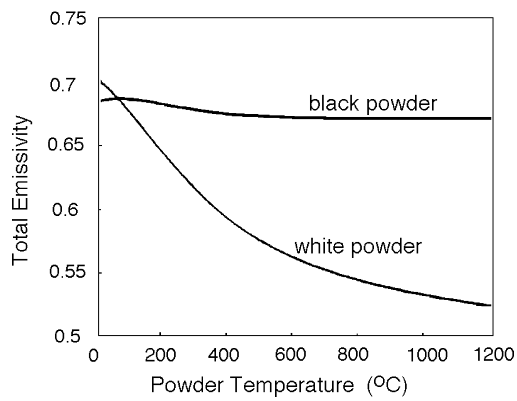
where α_η is the spectral absorptivity, and $e_{\eta,\mathrm{b}}$ the hemispherical spectral emissive power.

The extrapolated wavenumber distribution for the spectral absorptivity of a black powder is shown in *figure 5(a)*. This calculation process also incorporates the changes in the mean emissivity values which evolve from changes to the emitter temperature. This change is due to the shift of the maximum value of the Planck blackbody distribution with temperature. *Figure 5(b)* shows the variation of the mean emissivity $\bar{\varepsilon}(T)$ for black and white powders when the powder temperature varies. The magnitude of the error generated within these averaging processes can be estimated by determining the fraction of the total emitted energy which lies within the wavenumber range $\eta = 500$–$4\,000$ cm^{-1} covered in the measurements. For burner surfaces with temperatures between 700 °C and 950 °C, the fraction of the total energy emitted is within the range 0.7–0.8. This result suggests that the averaging process used to extend the range of spectral properties will yield reasonably accurate results—if no large spectral variations occur outside the measured wavenumber range.

The assumption that "*complete*" combustion takes place within the burner enables the partial pressure of the water vapour and carbon-dioxide components of the flue gas to be calculated. By applying the method proposed by Kudo [15], these pressures were then used to estimate the spectral absorption coefficients α_η. This method is based on the use of an Elsasser model which is used in conjunction with the Edwards' [7] wide band model. More information on the estimation procedure is given by Kögl [5]. The bands of particular interest were the carbon dioxide bands at 2.7, 4.3 and 15 µm; the water vapour bands at 2.7 and 6.3 µm and the water vapour rotational band at low wavenumbers.



(a)



(b)

Figure 5. Extrapolated information on the spectral absoptivity of the powders. (a) The extended wavenumber range of black powder. (b) The variation of the mean emissivity over the powder temperature for black and white powders.

The region between the flue gas layer and the powder coating contains air which does not actively participate in the energy transfer process. Within the analysis all of the energy lost from the system is assumed to pass through the four vertical planes which surround the burner and powder coated surfaces. These planes were modelled as isothermal black surfaces at ambient temperature.

6. RADIATION EFFICIENCY OF THE BURNER AND EFFICIENCY OF THE POWDER CURING PROCESS

Measurements from the burner tests were used in the analytical model to calculate the radiation efficiency of the burner and the overall efficiency of the curing process.

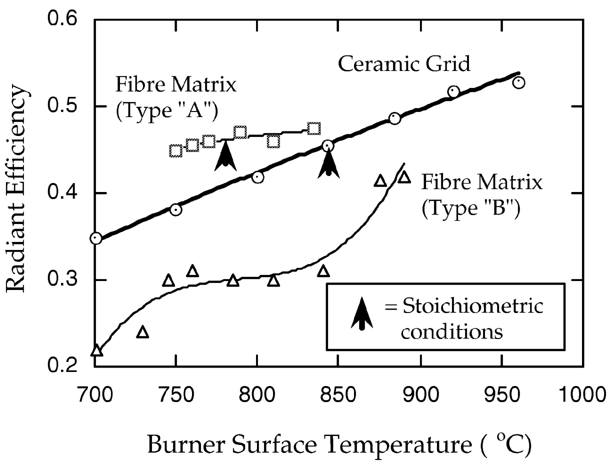


Figure 6. Calculated values of radiation efficiency for three different types of burner.

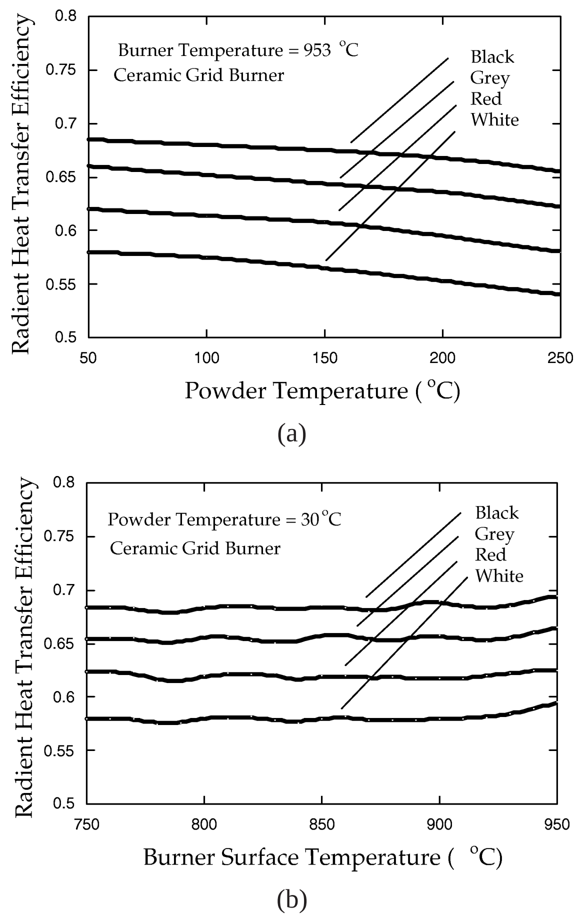


Figure 7. Predicted radiant heat transfer efficiency for different coloured powders with (a) varying powder temperature and (b) varying burner temperature.

The radiation efficiency is a distinctive characteristic of the burner. The total energy radiating from the burner was calculated on a plane located at the lower boundary of the flue gas layer. The information used in this calculation was presented in *figures 1* and *2*, the calculated values for the burner's radiation efficiency are shown in *figure 6*. The main trend emerging from these results is that the radiation efficiency of the burner increases with its surface temperature which in turn increases with the decreasing excess air factor. It is expected that this efficiency will continue to increase with decreasing values of the excess air factor until the increasing volumes of unreacted gas start to cool the burner's surface. No evidence of this maximum was found in these tests, presumably this is due to limitations in the maximum air excess factor available. Most burners operate close to stoichiometric conditions. The results show the radiation efficiency of the ceramic grid and one of the fibre matrix burners at this condition is 45 %.

An examination of previous investigations into burner performance shows that the values predicted in *figure 6* are within the expected range of values. Singh et al. [8] in a theoretical investigation examining the importance of flame location within a porous radiant burner, predicted a radiation efficiency of 42 % when the flame is located optimally in the middle of a burner. Tong and Sathe [9] have predicted comparable values in a similar analysis. During the testing of a gas heated infrared dryer Mattson et al. [10] obtained radiation efficiencies in the range 36–42 %. Much lower efficiencies were reported by Kiiskinen and Edelman [11] who investigated the radiation efficiency of a ceramic grid burner. The efficiencies reported in their work were 22 % with an air fuel ratio of 1.1 and only 12 % when the air to gas ratio was reduced to 1.4.

An analysis of the results from the simulation shows that only 10 % of the radiation reaching the coated surface originates from the flue gas. The low level of energy generated by this mechanism justifies, in part, some of the approximations made in the organisation of the tests and in the analysis. These approximations include the use of a small test oven and the definition of the flue gas layer.

The efficiency of the radiant heat transfer between the burner and the powder coated surfaces is shown in *figure 7(a)* and *(b)*. The efficiency of the energy transfer process is primarily influenced by the spectral properties of the powder coating. These results also show that the radiant heat transfer efficiency is effectively independent of the burner surface temperature (*figure 7(b)*). This lack

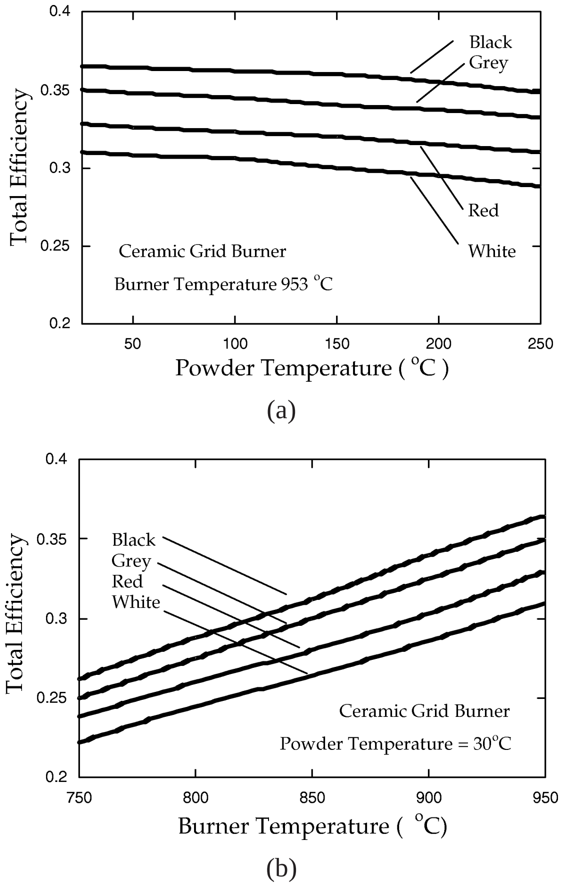


Figure 8. Predicted values for the total energy transfer efficiency for different coloured powders with (a) varying powder temperature and (b) burner temperature.

of influence is caused by the negligible effect which the wavenumber has on the spectral absorptivity within this temperature range. The burner surface temperature has a significant effect in defining the overall total efficiency of the process (*figure 8(a)* and *(b)*).

The results given in *figure 8(a)* show that when the burner temperature is constant, the total energy transfer efficiency decreases with increasing powder temperature. During the curing experiments, the temperature of the powder coating increased (*figure 3*) and, consequently, the instantaneous value of the total efficiency $\eta_{tot}(t)$ continuously decreased. This change in the total energy transfer efficiency during the curing process can be examined by defining a process efficiency η_P which relates chemical energy expended up to a time t_P to the net radiant heat that has been transferred to the powder:

$$\eta_P = \frac{\int_0^t Q_{net}(t)\,dt}{Q_{chem} t_P} = \frac{1}{T}\int_0^{t_P} \eta_{tot}(t)\,dt \qquad (6)$$

The process efficiencies calculated using this procedure are similar to those already given in *figure 8(a)*, where it was shown that the total efficiency decreases by only about 2–3 % when the powder temperature increases from 25 °C to 250 °C. Thus the integrated mean efficiency η_P of the curing process as defined in equation (6) can be approximated with the mean value of total efficiency in *figure 8(a)*. For a burner temperature of 850 °C the process efficiency η_P for different coloured powders was found to vary between about 25–30 %.

Most of the existing infrared burner studies have been directed towards the drying of paper and direct comparison with results for the curing of a paint surface may not be wholly appropriate. In paper drying, the quasi-static nonparticipating air volume is replaced by a region which has strong convection currents and significant vapour concentration gradients. The influence of these effects is unknown and, consequently, these comparisons should be accepted only as a guide. Lemaitre and Glise [12] reported total efficiencies for a gas heated infrared dryer of 35 % and for an electrically heated unit of 25 %. In a theoretical analysis Lampinen and Sievanen [13] calculated total efficiencies for a gas infrared drier to be in the range 24–37 % when drying increasing paper thicknesses. Leema [14] using the same experimental facility to that described earlier, has reported total efficiencies between 38 % and 47 % in tests which investigated the drying of coloured cementacious weather boards.

The results presented in *figure 8* show that the overall efficiency of the curing is highest at the greatest burner temperature and it could be assumed that the process should therefore be conducted at the highest possible temperature. This line of reasoning ignores the quality of the coated surface. The quality control tests normally performed on cured surfaces are highly subjective. These tests tend to focus on the determination of properties, such as appearance, adhesion between the coating and substrate and the flexural strength of the coating. Quality control tests were performed on all of the test samples, the main conclusion drawn from these tests was that the coatings cured with high burner temperatures and greater curing speeds tended to be of poorer quality. Good quality coatings were obtained in those tests where the burner fuel mixture was slightly rich or was close to stoichiometric conditions.

7. CONCLUSIONS

The efficiency of energy transfer from a gas fired infrared heater to a powder coated surface during curing has been calculated. This calculation uses the results from tests on gas burners where energy flows were measured and tests used to ascertain the spectral radiative properties of the powder. All of these results were incorporated in a Monte Carlo model of the heat transfer process.

A ceramic burner head was used in most of the tests. The radiation efficiency of this burner was 47 % at stoichiometric conditions. The maximum total efficiency of energy transfer between the gas supply and powder (37 %) was obtained using this burner and occurred when the excess air factor had its lowest value (0.8) and the burner temperature had its greatest value (950 °C). The test results indicated that the burner temperature would continue to increase if lower values of the excess air factor could have been obtained. Quality tests conducted on the cured product however demonstrated that operation at these high temperatures would be of limited value since the condition of the cured surface had started to deteriorate. These tests showed in that the quality of the cured powders depended strongly on the rate of heating but no simple relationship between these parameters was established. Tests at stoichiometric conditions produced good quality surfaces and the total efficiencies ranged from 30 % for black powder to 25 % for white powders. The other types of powder would produce a similar range of efficiencies.

Some of the radiative property measurements may have significant errors. In the spectral measurement of the powders' absorptivities up to 30 % of the radiation incident on the powdered surface did not fall within the range of measured values. It is unclear if the use of the extrapolated average value in these regions is realistic. A further area of concern is the total emissivity of the burner surface which could not be accurately obtained. The approximations used in the simulation to define the flue gas radiation will not have a significant effect on the efficiency calculations since the flue gas contributes less than 10 % of the radiation incident on the powdered surface.

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REFERENCES

[1] Dick R.J., Heater K.J., McGinnis V.D., McDonald W.F., Russell R.E., Comparison of the effectiveness of electric ir and other energy sources to cure powder coatings, J. Coatings Technology 66 (1994) 23–38.

[2] Gulnick J.R., Curing a new breed of coatings: How infrared ovens can be tailored to today's water borne and powder coatings, Products Finishing 58 (1994) 44–55.

[3] Lampinen M.J., Ojala K.T., Koski E., Modelling and measurement of infrared dryers for coated paper, Drying Technology 9 (1991) 973–1017.

[4] Mattson P., Pelkonen J., Riikonen A., Infrared drying of coated paper, Paper and Timber 72 (1990) 347–349.

[5] Kögl M., Curing of powder coatings with infrared radiant heaters: determination of the efficiency of the radiation heat transfer process, University of Auckland, Department of Mechanical Engineering Report, PME No. 96–26, 1996.

[6] Siegel R., Howel J.R., Thermal Radiation Heat Transfer, 2nd Edition, Hemisphere, Washington, 1981.

[7] Edwards D.K., Radiation Heat Transfer Notes, Hemisphere, Washington, 1981.

[8] Singh S., Ziolkowski M., Sultzbaugh J., Viskanta R., Mathematical model of a ceramic burner radiant heater, in: Proc. of ASME Fossil Fuel Combustion Symposium, Houston, 1991, pp. 111–116.

[9] Tong T.W., Sathe S.B., Heat transfer characteristics of porous radiant burners, J. Heat Tran. 113 (1991) 423–428.

[10] Mattson P., Pelkonen J., Riikonen A., Infrared drying of coated paper, Paper and Timber 72 (1990) 347–349.

[11] Kiiskinen H., Edelman K., The use of ceramic gas burners in paper drying, in: Proc. of Helsinki Symposium on Alternate Methods of Pulp and Paper Drying, PI-KCL Pira, 1991, pp. 425–436.

[12] Lemaitre A., Glise D., Radiation heating to increase machine production: Comparison of various technologies, in: Proc. of the Helsinki Symposium on Alternate Methods of Pulp and Paper Drying, 1991, pp. 405–424.

[13] Lampinen M.J., Sievanen M., An analysis of the efficiency of a radiative dryer, in: Proc. of the 6th International Drying Symposium, 1988, pp. 195–202.

[14] Leema E., The use of gas infrared heaters to modify the surface characteristics of a range of materials, M.E. Thesis, University of Auckland, 1998.

[15] Kudo K. et al., Improvement of analytical method on radiative heat transfer in nongray media by Monte Carlo method, Heat Transfer—Japanese Research 22 (6) (1993) 2255–2260.