Computational Fluid Dynamic (CFD) Modeling and Validation of Temperature Distribution in the Infrared Oven

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Abstract

Infrared (IR) process heating has been successfully employed to intensify thermal efficiency in various industrial applications. Although radiation is the most dominant mechanism in the infrared oven, its efficiency depends on the material's radiation properties. In this study based on ANSYS CFX 3D Model coupled with the P-1 sub model of a catalytic infrared oven were developed to study the effect of these properties and a convective oven was also modeled to study flow regimes through comparative methods. It was found that modelling results shown in comparison with published data can clearly simulate the performance of both ovens. These results confirmed that the IR oven has better efficiency than the other particularly for large objects having high emissivity. Moreover, mode simulation can indicate some process heating problems on curing powder coated low-conductivity material such as cracks on the edge in powder coated MDF. Finally, the results can provide a baseline for process engineer to design the infrared process heating and may also be used to retrofit existing ovens for better thermal distribution.

Keywords: CFD, infrared process heating, radiative heat transfer, temperature profile, energy efficiency

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1. Introduction

Process heating plays a vital role as a fundamental component in industrial manufacturing, where its energy consumption can be to 15% of the total production cost (Industrial Heating Equipment Association and the U.S. Department of Energy, 2001). Electricity and fossil fuel based substances are the primary energy resources for the processes and the choice depends on what is appropriate for the application.. The examples of process heating operations are drying, curing, baking, smelting, annealing, metal heating and melting which the first three applications were taken into consideration in the detail.

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Process heating applications and operations

Moisture removal systems know as drying plays a key role in food preservation, agriculture, textile, and glass industries. Hot air with low relative humidity or infrared (IR) drying can lead to evaporation of the moisture. The former may affect undesirable physical and chemical change due to high drying rate (Lewicki, 1998) and (Kowalski and Musielak, 2007), while implementation of IR radiation can help shorten drying times up to 50%, proven by the study of Lewicki (2004) on infrared drying of apple slices, Glouannac et al. (2008) on infrared-convective drying of hydrous ferrous sulphate and the U.S Department of Energy or DOE (2003) on infrared curing of powder coated metal.

Applied heat for the purpose of chemical reactions within the target pieces is called curing; for example, chemical cross-linking reaction of a thermoplastic or a thermoset polymer is triggered by heating inside a curing oven. This technique is extensively used in the powder coating system and can be achieved with either convective or radiative heating. A number of studies conducted on the integration of infrared heating with the traditional convection oven for enhanced heating performance showed hybrid system can offer more advantages than independent convection heating (IHEA, 2011) and (DOE, 2003). Moreover, the coating quality can be improved and some problems regarding non-conductive coating, for example, cracks on edges in powder coated medium density fiber board or MDF can be solved (Chapman, 2007).

Baking combines the functions of drying and curing and is utilized for cooking foods or bakery products. Most ovens are of the forced convection type where its temperature distribution depends on moving hot air and sometime may be influenced by radiative heat transfer. There are a great deal of baking ovens used in homes and industry; therefore, several scientists investigated the effect of flow regime with temperature profile inside this oven using either computer based simulation or measurement (Khatira, 2011), (Chhanwala et al., 2010) and (Therdthai et al., 2003).

Radiative and convective heating

In the infrared oven, there are two heat transfer mechanisms playing vital roles, convection and radiation. The former requires movement of fluid such as air, gases or liquids to convey heat to the target pieces; while, the object can directly absorb infrared energy from the heating elements as the rays are transferred through electromagnetic wave with insignificant energy loss. The IR technique is probably a key to enhance the ability of convection ovens. This claim could be supported by various published literatures.

With regard to complex geometries, convection seems better because radiative heating is limited by line-of-sight. Because the rays cannot be refracted in a medium, the energy can only be delivered from sources to a surface located a direct line of sight and cannot travel over obstacles in a complex shape. However, IR radiation may be more appropriate rather than convective heating in some operations, particularly when the whole part does not require to be heated, such as curing of powder coating. This is because infrared energy cannot penetrate deeply into the surface but a large amount of energy will be absorbed by its surface (DOE, 2003). It should be noted that in cases with high heat capacity, the IR technique could be used to reduce dwell time; for instance, curing powder coated massive parts such as engine blocks, construction beams and hydraulic excavators. This claim can be supported by the case study from IHEA (2011) which says heat-up cycle can be shortened by 37% and energy consumption can be reduced by 26% when integrated IR system.

Although an infrared heating system tends to be a higher investment cost than the other, it provides more energy efficiency, higher flexibility and lower operational cost. Glouannacet et at. (2008) and IHEA (2011) suggested that the hybrid system could improve process flexibility because it is easy to control temperature, has a fast response time and can deal with material and size variation. The electric IR emitter can be suddenly switched off in a second during non production, contributing to lower operational cost. 48% of the dwell time and 63% of energy bill can be reduced in the hybrid process drying of vegetables (Hebbar, Vishwanathan and Ramesh, 2004). Moreover, the environmental perspective; for instance, CO_2

reduction can be achieved in this system as well as low energy consumption.

Equipment sources of infrared

There are three types of the infrared heater classified by IHEA (2011); electric emitter, gas fired emitter and gas catalytic emitter shown in Fig. 1.

Fig. 1. a) Electrically infrared oven Heraeus,
b) Ceramic fibre gas fired infrared oven from Maywick,
c) Catalytic gas infrared oven from Infragas

With regard to advantages and disadvantages of these heaters, the electric emitter seems to be the easiest to control in that every IR wavelength range regarding ISO 20473 such as near-infrared (0.76µm-3µm), medium-infrared (3µm-8µm) and far-infrared wavelength (50µm-1,000µm) can be generated and its intensity can be rapidly adjusted, while the others can produce only the MIR and FIR wavelength range because gases IR intensity is limited by the air-gas ratio. However, the NIR wavelength range seems to match the absorption bands of most organic materials. To substantiate this claim, the study of Viscarra and McBratney(1998) presented that soil clay and water content have absorption bands conforming to four wave lengths which are 1.6µm, 1.8µm, 2.0µm and 2.1µm, which is consistent with the NIR wavelength range. In some process heating, flammability may be the major contribution to equipment selection; for instance, solvent-containing material, wood, plastic and paper; in which case, the electric emitter and flameless catalytic gas emitter seem more appropriate due to their flameless character. In terms of economics, both the gas-fired infrared and catalytic IR gas heaters are cost effective as natural gas and propane have lower price than electricity.

Process heating efficiency improvement tools

A high level of process heating performance can be defined as an ability to achieve the highest product quality with the lowest energy consumption and negative impact to environment under constrains. From the point of view of engineering applications, the process efficiency can be enhanced by several methods such as pinch analysis, process heating assessment and survey tool (PHAST) and process temperature profiling.

The pinch analysis is typically employed to chemical processes to reduce the energy consumption by providing a systematic methodology for energy saving; for instance, heat recovery systems, effective energy supply methods and optimised process operating. The study of Bergek (2011) clearly presented the merits of pinch technology which heat recovery concept has been analysed and employed in curing and drying oven in the powder coating system,contributing 30% cutting of energy cost expense and 25% reduction in carbon dioxide emission compared to 2010.

Another method to improve process heating efficiency is PHAST which was developed by the U.S. Department of Energy’s Industrial Technology. This technique can help managers or engineers to identify and evaluate improvement opportunities of currently process heating in fire furnaces, ovens, heaters, kilns or melters which rely on a fossil fuel base or electricity (DOE, 2003). The major advantages of this software are in reporting of overall energy consumption and cost contribution in or individual equipment; but it can also perform “what-if” analysis under different operating conditions or different fuel sources which can be significant for energy saving, enhancing productivity and improving energy efficiency of the process heating (Thekdi, 2007). Both pinch analysis and PHAST tend to be significant to process heating performance with regard to quantity improvement such as amount of energy saving and increased productivity; however, the quality of products are not enhanced.

The temperature profiling influences not only the potential thermal efficiency but also dominates the product quality variation. Temperature profiling inside the industrial ovens can be typically performed by measuring with thermocouples or by computer aided finite-element analysis. The former technique can be performed by attaching thermocouples on the part's surface at different locations and/or in the air, then the temperature data will be recorded by data logger and interpreted to temperature-time curve through software (Offley, 2011). The latter method is computer-based simulation has proven advantages in investigating fluid flow behaviours in several industrial processes, particularly in harmful environmental conditions such as toxic interactions or extremely high temperature processes. This computing technique, known as computational fluid dynamic (CFD), is also employed to investigate temperature distribution in various sectors such as the food industry, ultraviolet disinfection and baking processes where there is interaction between convective and/or radiative heat transfer. However, there are clearly some problems with the accuracy of the CFD modelling results, which still tend to be controversial because it depends on many factors such as performance computational resources, the accuracy of mathematic equations and physical properties which must be corrected in order to minimized error and achieve the most accurate results(Wong, Zhou and Hua, 2007).

CFD applications

There is several industrial applications which employ CFD techniques to optimise processes and retrofit current designs. These include powder coating system, water treatment systems and industrial process heating. Regarding the powder coating process, a large amount of research focuses on investigation of flow of powder particles flow under electrostatic charging inside sprayed room prior entrance the curing oven (Shah et al., 2006; Ye et al. 2003). Moreover, this computer-based tool is an effective method to predict behaviour and performance of various type of heat exchangers particularly in the design and optimization phase; for instant, fluid flow calculation, fouling, pressure drop and thermal analysis (AslamBhutta, M.M. et al. (2012). In recent time, CFD has been increasingly applied to food processing operation even in domestic or industrial application such as drying, sterilisation, refrigeration, storage and mixing (Norton and Sun, 2006; Xia and Sun, 2002).

CFD radiation models

There is also enormous development of commercial CFD codes to investigate fluid flow problems or thermal investigation of which ANSYS CFX, FLUENT, PHONICS and OpenFORM (Norton and Sun, 2006) are the main examples of currently commercial CFD software packages. Most of the research focuses on integration of these CFD packages for thermal analysis in forced or natural convection ovens where convection heat transfer plays the greater role (Therdthai et al., 2003 and Khatira et al., 2011). However, radiative heat transfer seems to dominant at high temperature conditions, over 600K (Therdthai et al., 2003; Mistry et al., 2006; Abraham and Sparrow, 2004; Chhanwala et al., 2010). There is relatively little research concerning radiation heat transfer; although these CFD programs offers radiation models such as the Rosseland model (RSM), the P-1 model, the Discrete transfer radiation model (DTRM), the Monte Carlo model (MCM), the Discrete Ordinates model (DO) and Surface-to-surface model (S2S) to simulate radiative participating problems , whose results accuracy can be improved.

Studies by Mistry et al. (2006), Wong, Zhou and Hua (2007) and Chhanwala et al. (2010) suggested that the DO model provides the most accurate results for slid-mesh simulations in continuous baking processes and U-turns because both the media participation and surface-to-surface radiation have been taken into account, while S2S considers only the latter. That is, radiation properties such as absorption and scattering are taken into consideration in the DO model but all absorption, emission or scattering are neglected in the S2S model (Chhanwala et al., 2010) as a result the computational time of the S2S model is two time faster than the DO approximation and the S2S model is also suggested for electrical oven modeling (Mistry et al., 2006).

With regard to P-1 and DTRM radiation models, both work reasonable with the optical medium to large thickness particularly combustion applications (Ilbas, 2005; Sazhin et al., 1996; Kontogeorgos, Keramida and Founti, 2007). Some researchers share the same view about the P-1 model that although this model seems suitable for industrial environments, it may generate over-predicted radiative results when employed with localized heat sources (Sazhin et al., 1996) and (Ilbas, 2005). Moreover, the P-1 and DTRM shared the same assumption that all surfaces are diffuse which occurs when the surface is rough as a result of reflection in all direction with no preferential direction of reflection. Another assumption is gray radiation and both neglect the effect of scattering. With regard to computational time, although the error of DTRM model may be reduced by enhancing the number of rays, a large number of rays contribute to CPU demand; and therefore, the P-1 model seems faster than the DTRM model (Ilbas, 2005). Finally, the P-1 model can be significantly better for objects which have complicated geometries with curvilinear coordinates (Ilbas, 2005) and it also provides reasonable results validated bydirect measurement in a coal based furnace (Sazhin et al., 1996).

Furthermore, several researchers have concentrated on exploring issues of temperature distribution prediction and validation in forced convection ovens particularly in bread-baking ovens. One of the most important criticisms of the bread baking process is that non-uniform heating affects bread's quality, such as colour and weight loss (Chhanwala et al., 2010; Therdthai et al.,, 2003). There is, however, relatively little research into predictions of the temperature profile in a catalytic gas infrared curing oven for powder coating systems.

There is also relatively little research into predictions of the temperature profile in the radiative heating circumstance; moreover, a comparison of the four radiation models, namely RSM, P-1, DTRM and MCM has not been performed for the infrared heating process.

The present work aims to study of effects of thermal radiation on heating products inside the infrared oven, with particular attention being paid to the validation of available radiation sub models provided by CFX-radiations with data provided by the industry. However, the 3D CFD model was developed to study several factors contributing to heating performance such as radiation properties, material and flow characteristic. The satisfactory computer based results validated by other published literature can also be used to modify oven configuration for better heat distribution, cost reduction and product quality enhancement.

2. Methodology

The CFD simulations can be classified into two sections; the first section focuses on the infrared oven regarding the effect of radiation coupled with natural convection from object movement in a continuous process and exhaust air system, on heated parts. The CFX radiation models such as RSM, P-1, DTRM and MCM were studied, and the most appropriate model was selected for further studies. In this study, the factors affected heating performance particularly surface emissivity, material properties and shape were considered through comparative methods. Finally, the results were also critical analyzed regarding the practical process heating problems.

The second section focuses on forced convective heat transfer in heating similar objects. These computational results were evaluated with the first section in order to confirm the potential of radiation versus convection. Finally, flow characteristics may be significant factors for heating performance in the convective oven, so these were also studied, investigating three different flow characteristics, laminar, transient and turbulence respectively.

2.1 Geometry modeling

The catalytic infrared oven comes from Vulcan Catalytic Systems, which is the leading manufacturer of the gas fired infrared heating systems utilized within the process heating industry. The geometries were created using ANSYS DesignModeler with half-model symmetric in they-z plane as in Fig. 2.

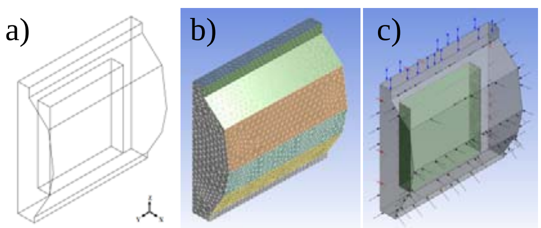


Fig. 2.a) Geometry of oven, b) Meshing and c) Boundary conditions of TP2

Table 1: Oven dimension and operating conditions

Oven segment	
Height (m) (z-direction)	3.470
Length (m) (y-direction)	2.835
Width (m) (x-direction)	2.590
Heater segment	
Model	P1640C
Number of heaters	16
Length (mm) x Width (mm)	406 x 1016
Area (m^2)	0.413
Gas power input (kW)	10.38
Natural gas, CH_4 flow rate (m^3/h)	1.00
Propane, C_3H_8flow rate (kg/h)	0.74
Firing condition	
Low fire temperature (K)	450
Pulse fire temperature (K)	755
High fire temperature (K)	811
Purging air flow rate (m^3/h)	1,7000
Conveyor speed (m/min)	2.00
Simulated test pieces	
TP1: Steel flat bar, ASTM A29, 16mm thick	
TP2: Steel bar, ASTM A29, 300mm thick	
TP3: Medium Density Fiber board, ASTM D4651, 18mm thick	

2.2 Meshing

Mesh optimization plays a key role in CFD studies, specifically which mesh is most appropriate to present the most accurate result with regard to the particular problems. The mesh size is constrained by computational resources, the particular research problems and desired accuracy of the result. It is clear that a very refined mesh provides more accurate result than large mesh, but it is limited by being highly time-consuming. In the same way, doing multiple sample-variations may require rapid solving time. Although simulation time can also be decreased by using better specification of working station, this research was limited with Window XP Professional with 3 GHz and 4 GB RAM. 3D meshes coupled with three different mesh sets as in Table 2 were employed in the study.

Table 2: Mesh selection

	Mesh size (cm)		Total mesh	Time
	Fluid	Solid		(min)
Mesh-1	12	0.55	62,286	3.47
Mesh-2	10	5	113,950	5.50
Mesh-3	5	4	462,234	40.00

Remark: Mesh-1 (TP-1, 3), Mesh-2 and Mesh-3 (TP2)

Mesh-1 and Mesh-2 provide suitable mesh sizes with a particular thickness and rapid computational time which is effective to generate 250 samples due to the dwelled time variation in both sections. Mesh-3 gives a very delicate mesh which is appropriate for studying flow characteristics in the second part with 3 type flow variations. In order to increase the solving accuracy with a large velocity shear strain rate, inflation layers were applied adjacent to the walls of the solid with 7 layers, expansion factor of 1.3 and maximum inflation thickness equal to the solid mesh size.

2.3 Domains

There are two domains, fluid and solid employed in the simulation.

Table 3: Domain properties

	Fluid	Solid	
Material	Air	Steel	MDF
Test piece	all	TP1,TP2	TP3
Density (kg/m^3)	N/A	7854	720
Specific heat capacity (J/kgK)	1004.4	434	1255
Initial temperature (K)	-	300	300
Radiation properties			
Option	clear	opaque	opaque
Diffuse fraction	1	1	1
Refractive index	1.0003	2.50	1.46
Absorption Coefficient (m^{-1})	0	0.82	0.965
Scattering coefficient (m^{-1})	0	0.82	0.035
Surface emissivity			
Black, CuO	0.75	0.96	
Blue, Cu2O3		0.94	
Red, Fe2O3		0.91	
White, Y2O3		0.90	

GGI mesh connection method was selected in domain interface for connecting solid to fluid domain which recommended by ANSYS in case of unaligned node.

CFX offer a wide range of turbulence models; however, Shear Stress Transport (SST) based was selected because it is suitable for non-equilibrium boundary layers, providing effective separation zone prediction and also high accuracy rather than the others in aerodynamic applications suggested by ANSYS. Moreover, the SST recommended by Williamson and Wilson (2009) for the heat transfer system with low Reynolds number is the infrared oven and natural convection (Zhang et al., 2007) , while k-ε seems over predict the velocity profile (Bardinaetal, 1997).

2.4 Boundary conditions

2.4.1 Radiation properties

Factors such as emissivity (ε), refractive index (n), absorption coefficient (α) and scattering coefficient (s)all play vital roles in radiative heat transfer simulation; meanwhile, the variation of diffuse fraction did not affect it, so it was set equal to one as assumption of diffuse object in the P-1 model. The air emissivity can be calculated according to advice of Swinbank(1963) as the equation below;

$$\varepsilon_{air} = C_{\varepsilon}(273.2 + T_{air})^2$$

where C_{ε}= 0.937 x 10^{-5} and $T_{air}$is in Celsius

However, in this project, the air emissivity was taken from the Streutker (2003) and Chhanwala et al. (2010) studies which highlighted the exact value of air emissivity as equal to 0.75, while the solid surface emissivity depends on surface coating colour which the black body was set as default.

Refraction is the bending of wave path due to a change in the speed of light when traveling from one medium to another. The bending angle can be expressed by the refractive index, ratio of light speed in vacuum to light speed in the particular medium and also related to surface reflectivity expressed by Hotwell, Siegel and Menguc (2011);

Dielectric materials: $\rho_n = (\frac{n_2-n_1}{n_2+n_1})^2$

Metals: $\rho_n = \frac{(n_2-n_1)^2+(k_2-k_1)^2}{(n_2+n_1)^2+(k_2+k_1)^2}$

where ρ_n=the reflective coefficient for nominal incident, n=reflective index and k=extinction coefficient.

The scattering concerns only diffuse reflected rays where the total reflection combines diffuse and specular reflected energy, so the scattering coefficient may be written as s + ρ_n = 1. In general, the coefficient parameters (α, ρ and τ) sum to 1.These relations depends on material properties; for example, the transport coefficient (τ) tends to be very significant in transparent media e.g. the value in air is near to 1, so all rays pass through the medium. Since the same coefficient in opaque materials is zero, α can be expressed in terms of ρ, which means the rays cannot pass through the medium but absorption and reflection will play a vital role. All coefficient values were taken from tests of paint coating on air craft material by Ohlsen and Etamed (1957) as the Fig. 3 below;

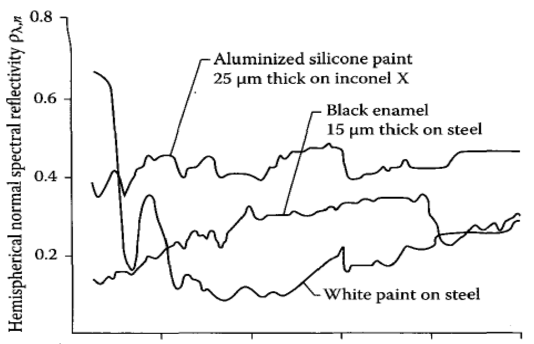


Fig. 3. Spectral reflectivity of paint coating, vertical dashed line stated Medium wave (4μm) in pulse fire (755K)

2.4.2 Convection properties

In terms of convection, heating efficiency mainly depends on flow characteristics which can be classified by Reynolds number (Re). Laminar flow occurred when Re < 2300, transient flow happened when 2300 < Re < 4000 and turbulent flow occurred when Re > 4000. Therefore, the boundary conditions can be defined as Table 4.

Table 4: Air velocity of convective simulation (boundary conditions) in the second section

	Re	Normal speed (m/s)
Laminar	900	0.00435
Transient	4,000	0.0193
Turbulent	10^6	4.828

2.5 Governing equations

2.5.1 Hear transfer equations

There are two heat transfer mechanisms interacting in the project. Radiation is possible between two surfaces and there can be some convective heat transfer from air purging combined with object movement, so total heat flux (q, w/m^2) can be expressed by $q = q_{conv} + q_{rad}$

Convection exchanges expressed by Newton's law of cooling, $q_{conv} = h(T_{source} - T_\infty)$ where h (W/m^2·K) is termed the convection heat transfer coefficient.

Radiation exchange between surface 1 and 2 in an enclosure as oven based on the equation suggested by (Incropera and Dewitt, 2002):

$$q_{rad} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_1 F_{12}} + \frac{1-\varepsilon_2}{\varepsilon_2 A_2}}$$

where σ is the Stefan-Boltzman constant (5.67x10^{-8} W/m^2·K^4), A = absorbed or emitted area (m^2) and F_{12} is the view factor.

2.5.2 Conservation equations

The conservation laws of mass, momentum and energy are principle of CFD numerical simulation for a continuous viscous fluid.

Mass conservation (continuity equation):

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j) = 0$$

Momentum conservation (Navier-Stokes):

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_j u_i + p\delta_{ij} - \tau_{ij}\right) = 0$$

Energy conservation:

$$\frac{\partial e}{\partial t} + \frac{\partial}{\partial x_j}\left[u_j(e+p) - u_i\tau_{ij} - q_j\right] = 0$$

2.5.3 Radiation models

The total radiation transfer equation (RET) presents the relationships between radiative coefficient parameters in the particular medium stated in Asinari (2007).

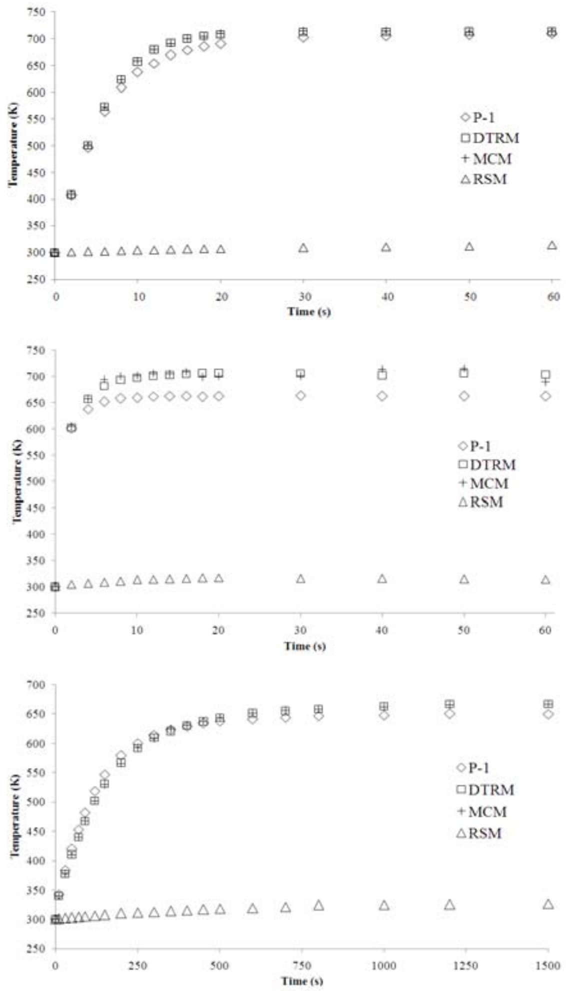


Fig. 4.Comparison of radiation models regarding object surface's temperature (y-axis) and heating cycle (x-axis) (from top to bottom) TP-1, TP-3 and TP-2

The CFX-radiation models were studied in theoretical terms and then evaluated using CFD results in order to identify the most suitable for future simulations. This infrared oven was designed for curing powder coating cured at a temperature of 530K; however, all models produced a huge difference from this curing point of powder, as the RSM generated a steady state at very low temperature, 310K while the other three generated quite high temperatures; more than 650K. The P-1 model has been selected as the simplest formulation providing moderate constructive results compared to the other three. Asinari (2007) suggested that the P-1 model may over-predict radiative heat transfer. Low temperature in case of the RSM simulation can be explained by Habibi, Merci and Heynderickx (2007)due to the effect of radiation limited to a variation of the radiation conductivity, while the P-1 model actually calculated transport equation. In terms of CPU demand, the P-1 model works reasonable well with the shortest simulation time, 25% faster than the DTRM.

Moreover, Habibi et al. (2007) and Asinari (2007) also suggested that the RSM is suitable for optically thick media with thickness ßL>3; in contrast, the P-1 is appropriate for optically medium with thickness ßL>1 (ß equal to σ·In10 and L is material thickness). If the optical thickness is small, there may be loss of accuracy dependingon the complexity of geometry. However, Sahin et al. (1996) noted that CFD simulation with this model generated results consistent with experiments of processes of thermal radiation in an industrial environment, particularly radiative exchange between gas and particle.

The P-1 model can be expressed by the equation below;

$$q_r = -\Gamma \Delta G$$

$$\Delta(\Gamma \Delta G) - aG + 4a\sigma T^4 = S_G$$

$$\Delta(\Gamma \Delta G) + 4\pi\left(a\frac{\sigma T^4}{\pi} + E_p\right) - \left(a + a_p\right)G = 0$$

3. Results and Discussion

3.1 Comparison of radiation and forced convection

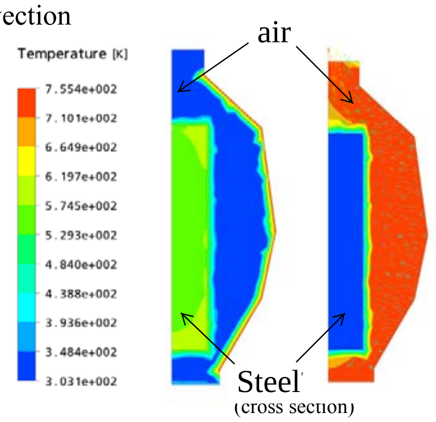


Fig. 5.Temperature distribution inside infrared oven (Left) and forced convective oven (Right) with 200s dwelled time

As can be seen from Fig. 5 (Left), the air temperature keeps cold while the object temperature increases as it directly absorbs infrared energy from heaters installed at oven's wall (presented with the red colour at755K in at the left figure. In this particular object, its temperature remained cold after heating for 200 seconds inside the convection oven, while the air is as high as the infrared source.

With regard to the temperature distribution of solid, it seems to be uniform both on the surface or inside in the convective heating. In contrast, non-uniform temperatures occurred with infrared heating particularly at the edge which seems hotter than the core temperature by approximately 19% until it became uniform at the specific temperature.

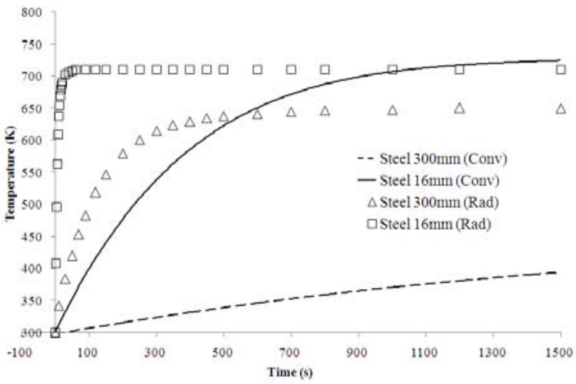


Fig. 6. Comparison of heat up rate at object's surface affected by radiation and convection in two thickness steels

Steel of thickness16mm and 300mm thickness were tested inside two different heat transfer mechanisms. It is clear that optically thick media took longer time to reach the target cured temperature at 530K than optical thin media and the infrared heating provided better efficiency. With regard to the infrared oven, the solid met the target temperature within 5 seconds and 132 seconds for optically thin and thick media respectively, while the other mechanism took 305 seconds and 115 minutes respectively.

In terms of heat up rate, the infrared oven also exhibited better performance with a temperature boost about 40-fold faster than convection heat transfer depending on the thickness. For example, thin material took 2.90K/s and 0.05K/s, while 47.83K/s and 1.08K/s for optically thick media in radiation and convection respectively.

3.2 Variation of materials

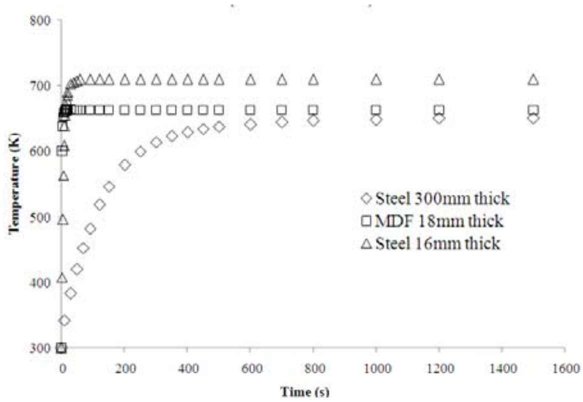


Fig. 7. Comparison of mean surface temperature of three different material types, heated inside the infrared oven.

Although dielectrics such as MDF have a higher absorption coefficient than steel, it exhibited lower steady stage temperature, lower than steel in optically thin medium. However, this may be partly due to the slightly different thickness between these two materials. It should be noted that the steady state temperature of MDF optically thin is similar to steel optically thick which is660K for the former and 650K for the latter.

Although the thickness difference between steel and MDF seems small, Bombard et al. (2008) stated that even the particle size of powder material in micron units seems to be significant in the infrared curing process. The absorption peak improved in the NIR wavelength range (0.76µm-3µm) when the powder particle thickness was increased, while the result seems opposite in the MIR wavelength range (3µm-50µm) which temperature tends to be decreased in higher thickness. Moreover, Bombard et al. (2008) also presented a temperature profile of steel and wood which states that the steady state temperature of wood is higher than steel around 300K for similar substrate thickness. Therefore, this result seems to be confirmation of the result in which the MIR wavelength was taken into consideration.

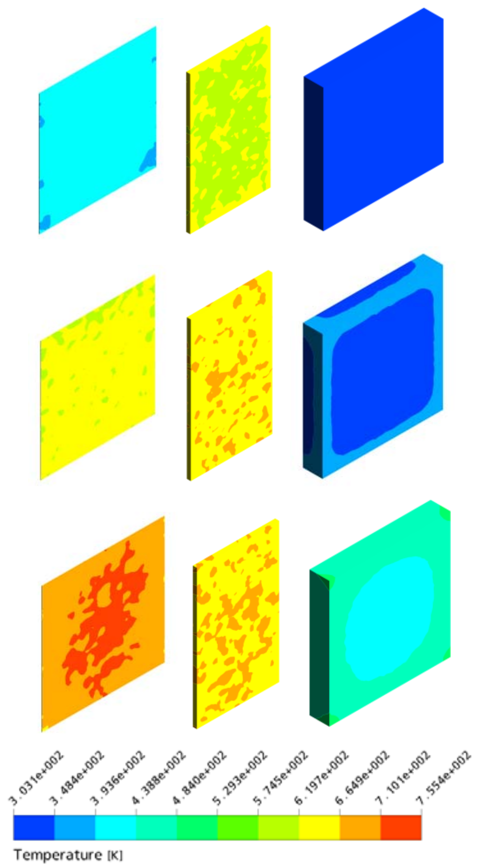


Fig. 8.Temperature profile of solid's surface inside radiative heating oven with pulse fire, 755K within 02s, 10s and 60s (From left to right: TP1, TP3 and TP2)

The surface temperature seems discontinuous when the thickness was decreased in both metal and dielectric as shown in Fig. 8. In contrast, temperature seems smooth distribution with high temperature happened at only corner and low temperature presented at the central in the optically thick.

3.3 Variation of surface emissivity

The different pigments affect absorption and scattering in IR-radiation. Although Fig.10 stated temperature distribution seems to be similar in both materials, black presented highest temperature and heat up rate followed by blue, red and white respectively. The different between highest (black) and lowest (white) mean temperature is 0.85% and 0.35% for steel and MDF. However, the relationship between the temperature and emissivity seems relevant with the theory that high emissivity leads to higher better heating performance.

Comparison of the powder coating on metallic and non-metallic objects heated by the NIR wavelength generated from 1750K heat sources was also measured by Bombard et al. (2008). The results are similar regarding in that the highest efficiency was obtained from the darkest pigment; however, the temperature difference between black-white was quite huge at20%. This huge difference may be explained by Offley (2011) in that the object was heated within different wavelength ranges. The object heated by the NIR wavelength revealed a difference between black-white pigments more than the MIR wavelength range, by about 64% as stated in Fig. 9.

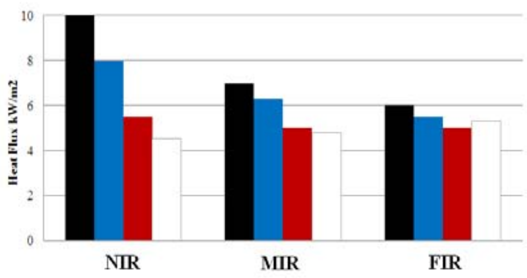
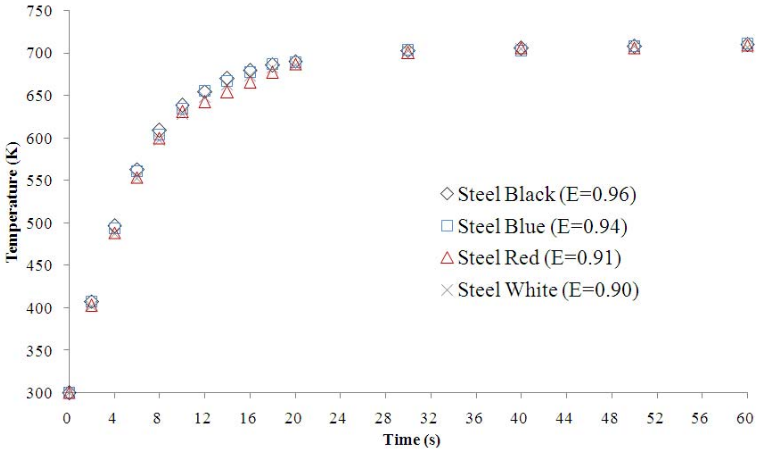
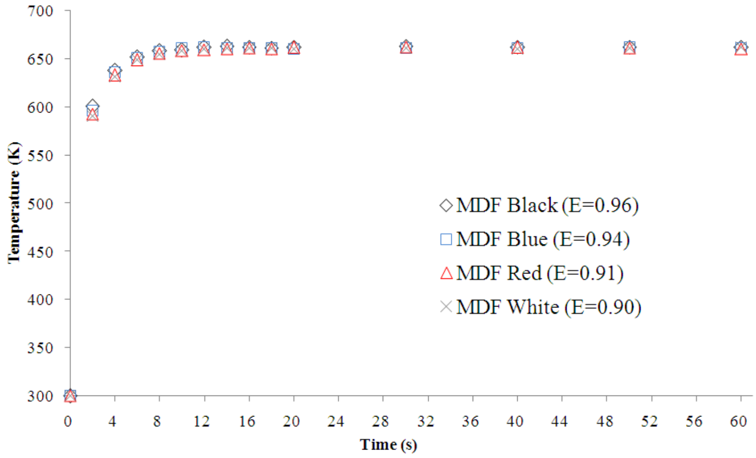


Fig. 9. Absorption of IR by powder coating at different wavelength (Offley, 2011)



Time	Temperature (K) Black E =0.96	Blue E =0.94	Red E =0.91	White E =0.90
0	300.00	300.00	300.00	300.00
2	407.70	407.27	402.70	402.34
4	496.26	493.30	488.62	487.08
6	563.01	560.27	553.63	551.96
8	608.61	603.78	599.95	597.43
10	638.16	633.96	630.61	627.63
12	654.42	655.67	642.17	647.54
14	669.57	667.21	653.73	662.60
16	678.89	676.93	665.29	673.41
18	685.42	686.46	676.85	682.30
20	690.28	689.00	686.50	686.04
30	702.87	703.11	699.82	702.11
40	705.62	702.76	705.50	704.60
50	707.49	708.05	705.42	708.09
60	709.79	710.85	708.89	707.05



Time	Temperature (K) Black E =0.96	Blue E =0.94	Red E =0.91	White E =0.90
0	300.00	300.00	300.00	300.00
2	600.54	596.30	592.36	590.82
4	637.88	635.91	633.08	631.84
6	651.87	650.77	648.83	649.02
8	658.07	657.26	655.89	654.65
10	659.31	660.86	658.90	658.22
12	661.83	662.10	659.70	660.01
14	663.07	661.58	660.34	661.00
16	662.65	661.71	661.03	660.83
18	661.39	661.71	660.52	660.95
20	662.64	660.59	661.85	660.60
30	663.54	661.29	661.94	661.04
40	662.42	661.57	661.82	660.44
50	662.40	662.01	661.01	661.61
60	662.40	661.63	660.67	662.35

Fig. 10. Comparison of temperature profile when the surface emissivity is varied from 0.90 to 0.96, TP1 (Top) and TP3 (Bottom)

The efficiency of heating by the NIR wavelength range source is supported by the study of Deans and Kögl (1999)who employed an infrared gas heater with a 1225K source temperature as a result of darker pigment provided higher efficiency with 5% error in the variation between black-white colour. Moreover, Stewart et al. (1999) stated the same range regarding the variation of wavelength or emitter temperature as Fig. 10. The high emitter temperature and the NIR wavelength presented a great deal of difference between the darkest and the lightest pigment, while this difference seems very small in the MIR and FIR wavelength range.

With regard to powder coating with white colour, they also suggested that lowest infrared absorbability may be influenced by concentration of titanium dioxide (Stewart et al., 1999). The infrared rays were scattered without absorbing IR-radiation in the visible light and the NIR wavelength range within creasing amount of titanium dioxide tending to reduce the absorbed infrared energy.

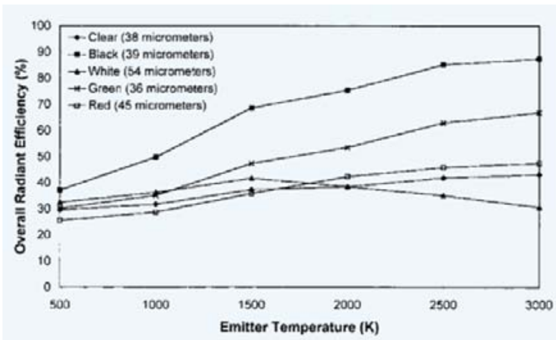
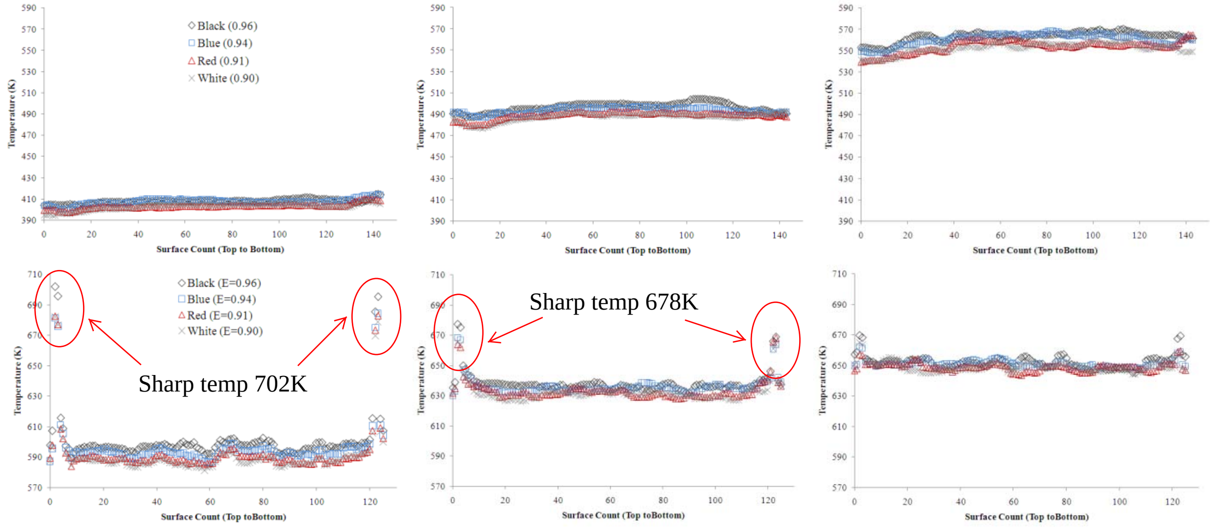


Fig. 11. Overall radiant efficiency of pigmented and unpigmented powder coatings vs blackbody emitter temperature (Stewart et al., 1999, p80)

3.4 Comparison with real world problems



(a) (b) (c)

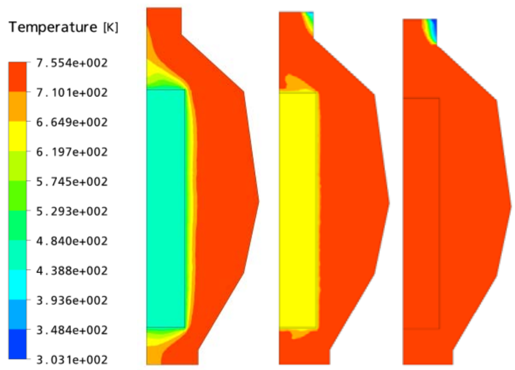
Fig. 12. Comparison of temperature profile across center of Steel 16mm (top) and MDF 18mm (bottom) with a) 02s, b) 04s and c) 06s cycles

The figures clearly show that the MDF has a sharp temperature gradient near its edge and that the magnitude was decreased by time, while this did not happen in the steel. One reason may be that the thermal conductivity (k) of MDF is poor, being185-fold lower than conductivity of steel, k_{MDF}=0.23 and k_{steel}=43. Therefore, radiative energy may accumulate at the surface in particular; moreover, this situation may be supported by the nature of IR-radiation in that radiative energy cannot penetrate deep into opaque medium, so most energy is absorbed and retained at surface.

Verbovena et al. (2003) and Chhanwal (2010) presented a similar result on surface heat transfer fluctuation at surface of bread. A particularly extreme temperature occurred near the corner which contributes to an excessive drying problem. This defect is consistent with the coating cracking occurred on the edges of powder coated heat sensitive materials such as plastics, wood panels or MDF boards.

Therefore, powder coating on these materials seems a challenge for the engineer due to having a low conductivity and which cannot tolerate high temperature. Speical processes have been designed, using integrated IR-radiation are designed (Chapman, 2007) or using low temperature curing e.g. UV-curable (Barletta and Bellisario, 2011) to deal with this problem and be cost competitive.

3.4 Variation of flow characteristic



(a) (b) (c)

Fig. 13. Comparison of the temperature profile of TP3 (Steel 300mm) heated inside the convection oven 20mins a) laminar, b)transient and c)turbulence

The radiative heating depends on radiation properties and the intensity of heat source, while for convective heating, flow characteristics must be taken in to consideration. Reynolds number is used to classify the laminar, transient and turbulence flow regimes and the Reynolds number was assume to fit in these ranges assuming of velocities 0.0043m/s, 0.0193 m/s and 4.828m/s respectively in each particular case.

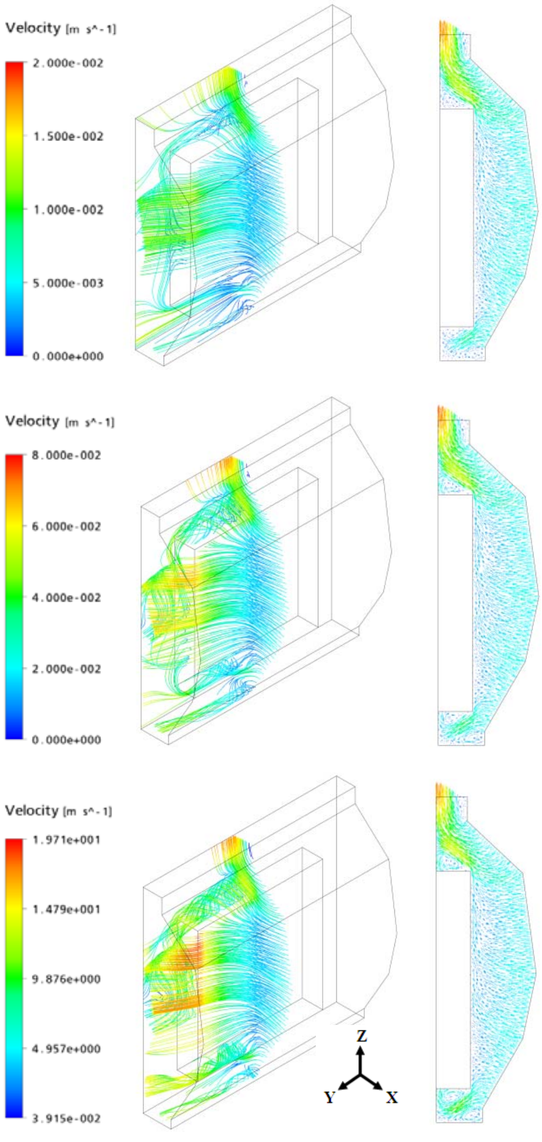


Fig. 14.Comparison velocity profile of convection oven a)laminar (0.00435 m/s), b)transient (0.0193 m/s) and c)turbulence (4.828 m/s)

Considerable differences of air velocity can be attributed to heating performance. As can be seen in the solid temperature profile from Fig. 14, the turbulence flow in Fig. 14(a) presented the highest temperature followed by transient and laminar flow respectively. In terms of velocity profile, all cases tend to have similar streamlines in which flow vectors travel from source in (–x) direction and then flow change to parallel object's surface in (+y) direction after hitting its surface with the highest velocity happening at the vertical solid edge before the air left the oven at the top opening of purging system.

4. Conclusion

CFD models integrated with RSM, P-1, DTRM and MCM radiation model were employed to study the object's and oven's behavior, for heating under the infrared industrial oven. The simplest radiation model as the P-1 was selected to perform the variation of material characters and emissivity due to recommendation by several researchers for the prediction of IR-radiation of medium optical thickness particularly in an industrial environment and providing constructive results with shortest simulation time. However, the data temperature seems to be over predicted compared with the powder coating cured temperature.

With regard to computational results, it can clearly discriminate between the traditional convection oven and the infrared oven which the latter seems more energy efficient. Moreover, the CFD technique helped engineers to enhance our knowledge of the effect of radiation properties and provided insight into the nature of radiative heating. Most results seem to conform to theoretical assumptions for both radiative and convective heat transfer circumstances; for example, thick material tends to have a slower heat up rate than thin objects and the darkest colour exhibits the highest radiative absorption, while turbulence flow showed better heating efficiency.

However, the radiative absorption characteristic of varied surface finishing pigments also depended on the wavelength range. Although the

CFD results stated tiny different comparison between heating black and white powder coated on TP1 and TP3, other researchers presented huge difference, it was due to the effect of the wave number in IR source which the NIR wavelength range seems to be very significant to this variation. Moreover, the CFD result can also be consistent to some realistic process heating problems.

With regard to limitations, the accuracy of computational result depends on simulation time; however, the research was limited by one semester. The error may be reduced, if exact value radiation properties were determined using a special device such as a spectrometer which can measure absorption coefficient of particular material and surface. Validation of these results with the other CFD software packages seem to be the other way to achieve a comparative approach; however, the teaching license prohibits comparison of the CFX-result with the other CFD codes.

Although CFD results seem reasonable compared to several studies, experiments should be performed to validate these result due to the several published studies conducted in different configurations. There are several research studies showing CFD result validation with experimentation. For instance, Williamson and Wilson (2009) and Mistry (2011) advised that the CFD results generated 10% and 6% of temperature error respectively, while Mirade et al. (2004) and Verbovena et al. (2003) stated 4.6°C error for air temperature and 0.5°C error for object temperature inside baking ovens.

This study may help engineers gain insight about implementing computer based tools such as CFD technique to deal with process heat transfer problems. However, CFX-radiation can be extended to other fields which can be taken in to account for future researches. For examples; the effect of the sun's radiation for thermal design in building which can be used to predict the effects on the temperature inside the building when shape, material and surface finishing are changed. Moreover, CFD methods coupled with radiation models can be employed to study porous medium which provide a great advantages for food industry as the core temperature must reach a set point to ensure the death of bacteria. Finally, simulating the effect of sun radiation on design solar cell panels can also be integrated this method.

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6. References

- Asinari, P (2007) *Radiation heat transfer: Basic physics and engineering modeling*, IL: the University of Illinois
- AslamBhutta, M.M., Hayat, N., Bashir, M.H., Khan, A.R., Ahmad, K.N. and Khan, S. (2012) 'CFD applications in various heat exchangers design: A review', *Applied Thermal Engineering*, vol.32, pp.1-12.
- Bardina, J.E., Huang, P.G. and Coakley, T.J. (1997) *Turbulance modeling validation testing and development: NASA Technical memorandum 110446*. CA.
- Bergek, C. (2011) *Energy efficiency opportunities within the powder coating industry (Energy audit and pinch analysis).* Sweden, GÖteborg: Department of Energy

and Environment, Chalmers University of Technology.

- Bombard, I. Laurent, P., Lieto, J. and Jeandel, G. (2008) 'A model of the infrared cure of powder coating based on surface absorptive in-situ measurement', *Journal of Coatings Technology and Research*, vol.5, no.3, pp.353-363.
- Barletta, M. and Bellisario, D. (2011) Effects of IR pre-curing conditions on wear resistance of metal flake powder coatings, *Progress in Organic Coatings*, vol.70, no.4, pp.273-286.
- Chapman, M. (2007) 'MDF Powder Coating: A practical update', *Powder coating magazine*, Vulcan Catalytic Systems.
- Chhanwala, N., Anishaparvina, A., Indranib, D., Raghavaraoc, KSMS. andAnandharamakrishnan, C. (2010) 'Computational fluid dynamics (CFD) modeling of an electrical heating oven for bread-baking process', Food Engineering, vol.100, pp.452–460.
- Deans, J. and Kögl, M. (1999) 'The curing of powder coatings using gaseous infrared heaters: An analytical model to assess the process thermal efficiency', *International Journal of Thermal Sciences*, vol.39, no.7, pp.762-769.
- DOE (2003) *Progressive Powder Coating: New Infrared Curing Oven at Metal Finishing Plant Increases Production by 50%*, DC: the DOE.
- Glouannac, P., Salagnac, P., Guezenoc, H. and Allanic, N. (2008) 'Experimental study of infrared-convective drying of hydrous ferrous sulphate', Powder Technology, vol.187, no.3, pp.280-288.
- Habibi, A., Merci, B. and Heynderickx, G.J. (2007) 'Impact of radiation model in CFD simulations of steam cracking furnaces', *Computer and Chemical Engineering*, vol.31. no.11, pp.1389-1406.
- Hebbar, H.U., Vishwanathan, K.H., and Ramesh, M.N. (2004) 'Development of combined infrared and hot air dryer for vegetables', *Journal of Food Engineering*, vol.65, no.4, pp.557-56.
- Hotwell, J.R., Siegel, R. And Menguc, M.P. (2011) *Thermal Radiation Heat* Transfer, 5th ed., CRC Press: FL, pp 88-99.
- IHEA (2011) *Maximize your convection oven by using infrared and Adding gas-fired infrared energy to a powder coating process: A decision –tree analysis.*
- Industrial Heating Equipment Association and the U.S. Department of Energy (2001) *Roadmap for Process Heating Technology*, USA.
- Ilbas, M. (2005) 'The effect of thermal radiation and radiation models on hydrogen–hydrocarbon combustion modelling', *International Journal of Hydrogen Energy*, vol.30, no.10, pp.1113-1126.
- Incropera, F.P. and Dewitt D.P. (2002) *Introduction to heat transfer*, 4th edition. Wiley: USA, pp.441, 748 and 768.
- Khatira, Z., Patona, J., Thompsona, H., Kapura, K. Toropova, V., Lawesa, M. and Kirkc, D. (2011) 'Computational fluid dynamics (CFD) investigation of air flow and temperature distribution in a small scale bread-baking oven', *Applied Energy*, vol.89, no.1, pp.89-96.
- Kontogeorgos, D.A., Keramida, E.P. and Founti, M.A. (2007) 'Assessment of simplified thermal radiation models for engineering calculations in natural gas-fired furnace', *International Journal of Heat and Mass Transfer*, vol.50, no.25–26, pp.5260-5268.
- Kowalski, J.S. and Musielak, G. (2007) *Heat and Mass Transfer during Convective and Microwave-Convective Drying of Porous Bodies Modelling, Numerical Simulation and Experiment*, Poland: Poznan University of Technology.
- Lewicki, P.P. (1998) 'Effect of pre-drying, drying and rehydration on plant tissue properties: A review', *International Journal of Food Properties*, vol.1, pp.1–22.
- Lewicki, P.P. (2004) 'Infrared drying of apple slices', *Food Science and Emerging Technologies*, vol.5, pp.353–360.

- Mistry, H., Ganapathisubbu, S., Dey, S., Bishnoi, P. and Castillo, J.L. (2006) 'Modeling of transient natural convection heat transfer in electric ovens', *Applied Thermal Engineering*, vol.26, no.17–18, pp.2448-2456.
- Mirade, P.s., Daundin, J.D., Ducept, F., Trystram, G. and Clement, J. (2004) 'Characterization and CFD modelling of air temperature and velocity profiles in an industrial biscuit baking tunnel oven' *Food and Research International*, vol.37, no.10 pp.1031-1039.
- Mistry, H., Ganapathisubbu, S., Dey, S., Bishnoi, P. and Castillo, J.L. (2011) 'A methodology to model flow-thermals inside a domestic gas oven', *Applied Thermal Engineering*, vol.31, no.1, pp.103-111.
- Norton, T. and Sun, D.W. (2006) 'Computational fluid dynamics (CFD) – an effective and efficient design and analysis tool for the food industry', *Trends in Food Science & Technology*, vol.17, pp.600-620.
- Offley, S. (2011) *IR Oven Temperature Profiling Lecture Presentation.*
- Ohlsen, P.E. and Etamed, G.A. (1967) *Spectral and Total Radiation Data of Various Aircraft Material.*
- Sazhin, S.S., Sazhina, E.M., Faltsi-Saravelou, O., and Wild, P. (1996) 'The P-1 model for thermal radiation transfer: advantages and limitations', *Fuel*, vol.75, no.3, pp.289-294.
- Shah, U., Zhu, J., Zhang, C. and Nother Senior, J.H. (2006) 'Numerical investigation of coarse powder and air flow in an electrostatic powder coating process', *Powder Technology*, vol.164, no.1, pp.22-32.
- Stewart, A.L., Carr, W.W., Williamson, V.A., Mc-Farland, E.G. and Hohnson, M.R. (1999) 'Characterization of infrared absorption by powder coatings on steel panels', *Journal of Coating Technology*, vol.71.
- Streutker, D. (2003) A study of the urban heat island of Houston. TX.
- Swinbank, W.C. (1963) 'Longwave radiation from clear skies', *Q. J. R. Meteorol. Soc.*, 89:339-448.
- Thekdi, A. (2007) Process Heating Assesspemt and Survey Tool (PHAST), USA: the DOE.
- Therdthai, N., Zhoua, W. and Aamczak, T. (2003) 'Two-dimensional CFD modelling and simulation of an industrial continuous bread baking oven', *Food Engineering*, vol.60, no.2, pp.211–217.
- Verbovena, P., Dattab, A.K., Anha, N.T., lincka, N.S. and Nicola N.M. (2003) 'Computation of airflow effects on heat and mass transfer in a microwave oven', *Food Engineering*, vol.59, pp.181-190.
- Viscarra, R.A. and McBratney, A.B. (1998) *Laboratory evaluation of a proximal sensing technique for simultaneous measurement of soil clay and water content*, Geoderma, vol.85, no.1, pp.19-39.
- Williamson, M.E. and Wilson, D.I. (2009) 'Development of an improved heating system for industrial tunnel baking ovens', *Food Engineering,* vol.91, pp.64–71.
- Wong, S.Y., Zhou, W. and Hua, J. (2007) 'CFD modeling of an industrial continuous bread-baking process involving U-movement', *Journal of Food Engineering*, vol.78, no.3, pp.888-896.
- Xia, B. and Sun, d.W. (2002) 'Applications of computational fluid dynamics (CFD) in the food industry', *Computers and Electronics in Agriculture,* vol.34, pp.5–24.
- Ye, Q., Steigleder, T., Scheibe, A. and Domnick, J. (2003) 'Numerical simulation of the electrostatic powder coating process with a corona spray gun', *Journal of Electrostatics*, vol.54, no.2, pp.189-205.
- Zhang Z., Zhang W., Zhai Z. and Chen Q (2007) 'Evaluation of various turbulence models in predicting airflow and turbulence in enclosed environments by CFD: Part-2: comparison with experimental data from literature', *HVAC&R Research*, vol.3, no.6.

7. Appendices

The appendices indicated in attached DVD consist of the following materials;

A1 CFD models

A2 CFD results

A3 Minute of meeting

A4 Weekly report

A5 Oven drawing and instruction manual

A6 Research documents

- Research plan
- Project work schedule
- Research proposal
- Literature review
- Poster presentation
- Leaflet IR process heating
- Master thesis final report
- Oral final presentation