COMPARISON BETWEEN FOUR RADIATIVE MODELS IN GLASS COOLING

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الملخص

في هذه الورقة البحثية تم إستخدام برنامج حاسوب جاهز (FLUENT) مُعد لغرض نمذجة ديناميكا الموائع لدراسة عمليات إنتقال الحرارة من الزجاج الساخن إلى الهواء المحيط به أثناء عمليات التصنيع عندما يكون إنتقال الحرارة بالإشعاع هو الطريقة الرئيسية لإنتقال الحرارة. يسمح البرنامج المستخدم بإستخدام عدة نماذج رياضية مختلفة للنمذجة ومحاكاة إنتقال الحرارة من الزجاج.

في هذه الدراسة تم إستخدام أربعة نماذج لإنتقال الحرارة بالإشعاع بهدف مقارنة نتائجها مع بعضها ومع نتائج تجارب معملية أجريت لهذا الغرض. النماذج التي تم إستخدامها عند نفس الشروط والظروف الحدودية هي: نموذج روزلاند (RO) ونموذج الاحداثيات المتقطعة (DO) ونموذج الإحداثيات الإنتقالية (DTRM) ونموذج (P-1). من خلال النتائج التي تم الحصول عليها وجد أن نموذج الإحداثيات المتقطعة (DO) يعطي نتائج أكثر دقة لدرجات الحرارة داخل سمك الزجاج وعلى سطحه بالمقارنة بالنماذج الاخرى كما أن نتائجه قريبة جداً من النتائج العملية عند نفس الظروف.

ABSTRACT

In this paper a Computational Fluid Dynamic modelling software package, 'FLUENT' [1], is used to simulate the heat transfer process from the soda-lime glass during the blank open phase of glass manufacturing when heat transfer by radiation is dominant. This software incorporates different radiative heat transfer mathematical models that may be applied, to solve the problem at hand. Four methods are used to solve the same model and their results compared with each other as well as with experimental work. The four approaches are Rosseland (RO), Discrete Transfer Model (DTRM), P-1 and Discrete Ordinates (DO) and in each case the same set of initial conditions have been applied to the model. The Rosseland RO and The Discrete transfer DTRM approximation with prescribed boundary temperature are found to be insufficiently accurate through all the thickness (surface to centre); The P-1 approximation is found to be sufficiently accurate except near the free surface. The Discrete ordinates (DO) is found to be very sufficient and accurate through all the thickness and near the free surface. The Discrete ordinates DO approximation gives results that are in excellent agreement with experimental result.

KEYWARDS: Fluid dynamic models (RO, DTRM, P1, DO); Soda-lime glass conduction; radiation, thermocouples.

INTRODUCTION

In radiative heat transfer analysis for soda lime-glass, the Rosseland RO and the P-1 approximations have been widely used in the numerical simulation of heat transfer in glass furnaces and forming processes, Viskanta and Song [2]. Other approximations such as the Discreet Transfer DTR, and Discreet Ordinates DO have also been used, however, their validities are not well confirmed and their limits of applicability need to be verified. The above four approximate methods are compared to the experimental result and their validities are scrutinised by cooling a 6 mm thick glass from 1100^{o}C to 500^{o}C by heat loss to ambient are kept at a room temperature of 20^{o}C in a time of 50 sec. Prior to performing the modelling and discussing the results, it is useful to consider the optical thickness of the glass in question as this is known to have an important effect on modelling the results. Previously published work has highlighted that each of the models behaves differently depending on the thickness and that only selected models are appropriate for modelling at particular thicknesses [3]. In all the reported numerical simulation methods, use of Rosseland and the Discrete Transfer models are generally accepted for glass thickness exceeding 10 mm. Viskanta and Song [2] however; examined the validity of the Rosseland model in stagnant glass layer and call for caution when applying it to glass melts less than 10 mm thick. In addition RO and DTR models are known to be erroneous near the boundary where the temperature and radiation field undergo sharp variations. For all depths of the glass melts of 10 mm thick the P-1 and the DO models give better results than the Rosseland and DTR models. When the depth of the glass melts is greater than 10 mm the DTR model gives almost the same results as the P-1 model.

The Discrete ordinates (DO) model is found to be very sufficient and accurate through all the thickness and near the free surface. The Discrete ordinates DO approximation gives results that are in excellent agreement with experimental result.

MATERIALS AND METHODS

Models used

In this investigation four different mathematical methods are applied to solve a model using the 'Fluent' software [1]. These models are: Rosseland (RO), the Discrete Transfer (DTRM), the P-1, and the Discrete Ordinates (DO). The model under examination is that of a hot soda lime-glass body radiating into the ambient air, this presents a heat transfer coefficient of 10 W/m^2 K. The thermal properties and initial conditions applied to the model are the same as those applied in the work published by Rawson [4], Curran [5] and Bauer [6]. A discussion of each of the mathematical methods is now provided.

The Rosseland radiation model (RO)

The Rosseland or diffusion approximation for radiation is valid when the optical thickness is greater than 30 mm. It is derived from the P-1 model equations, with some added approximations. The Rosseland model needs to solve one less transport equation for the incident radiation than the P-1 model and is prepare faster than the P-1 model and also requires less memory.

The discrete transfer radiation model (DTRM)

The main assumption of the DTRM is that the radiation leaving the surface element in a certain range of solid angles can be approximated by a single ray. The primary advantages of the DTRM are threefold: it is a relatively simple model, increased accuracy is achieved by increasing the number of rays considered, and it applies to a wide range of optical thicknesses.

The (P-1) radiation model

The P-1 radiation model is the simplest case of the more general P-N model; it is based on the expansion of the radiation intensity (I) into an orthogonal series of spherical harmonics. The P-1 model has several advantages over the DTRM. Firstly, the use of an easy to solve diffusion equation requires little demand on CPU time. The model includes the effect of scattering. For combustion applications where the optical thickness is large, the P-1 model works reasonably well. In addition, the P-1 model can easily be applied to complicated geometries with curvilinear coordinates.

The discrete ordinates radiation model (DO)

The discrete ordinates DO radiation model solves the radiative transfer equation for a finite number of discrete solid angles, each associated with a vector direction $\vec{s}$ fixed in the global Cartesian system (x, y, z). The DO model spans the entire range of optical thicknesses, and allows a range of problems to be solved, from surface-to-surface radiation to participating radiation in combustion problems. It can also provide solutions to radiation in semi-transparent media such as soda lime-glass Manthuruthil [7] and Sikri [8].

The non-grey implementation in the software is intended for use with participating media with a spectral absorption coefficient (α), which varies in a stepwise fashion across spectral bands, but varies smoothly within the band. Soda-lime Glass, for example, displays banded behaviour of this type Liu. [9] Carvalho [10]. For the purposes of the current investigation, this will allow the anisotropic semi-transparent nature of the model to be included in the simulation. However, the non-grey implementation assumes a constant absorption coefficient within each wavelength band. Gardon [3] and Rawson [11]

Modelling and simulation parameters

Each of the four mathematical techniques discussed will be applied to a model to predict the heat loss by radiation from soda lime-glass when it is in the air. The simulation results will be compared with practical results, discussed later. Therefore the model used is constructed in such a way as to reflect the practical work carried out.

The analysis to be performed is of a piece of soda-lime glass with a thickness of 12 mm. Starting with an initial temperature of 1100 °C the heat lost by radiation from one surface of the glass to the surrounding environment, which consists of air (20 °C), over a period of 50 seconds is calculated. This is approximately the time it takes for the glass to cool from 1100 to 500 °C in air; this will be seen later. The temperature at the centre of the glass (at a depth of 6 mm from the surface), from the glass surface is also calculated. Tables (1 to 5) present the simulation parameters and material properties required for the creation of the model and Figure (1) shows the physical layout of the model.

Table 1: Parameters used and their settings

Parameter	Settings
Space	2D
Time	Unsteady, 1st-order implicit
Viscous	Laminar
Heat Transfer	Enabled
Solidification and melting	Disabled
Radiation	Discrete ordinate model

Table 2: Solver control equations

Equations	Solved
Flow	No
Energy	Yes
Discrete ordinates	Yes
Numeric	Enabled

Table 3: Bands of wavelengths and absorption coefficients, used by [11]

Bands	Absorption coefficient (α) m^{-1}	Wavelength (μ)
Band-1	23	0.8 - 2.25
Band-2	45	2.25 - 2.75
Band-3	100	2.75 - 4.3

Table 4: Initial, mould and air temperatures and properties used by [12], [4], [13]

Property	Units	Glass (fluid)	Air (fluid)
Density	(kg/m^3)	2500	1.225
C_p (Specific heat)	(J/kg K)	1350	1000
Thermal conductivity	(W/m K)	1.45	0.0242
Temperature	(^oC)	1100	20
Heat transfer coefficient	(W/m^2 K)	-	10
Absorption coefficient	(m^{-1})	23, 45, 100	-
Refractive index	-	0.5	-
Thickness	(mm)	6	20
Time	(Second)	50	50

Table 5: Summary of air properties [literature review]

Air properties	Density (kg/m^3)	Specific Heat (J/kg-K)	Thermal Conductivity (W/m-K)	Heat Transfer Coeffi. (W/m^2-K)	Initial Temp. (^oC)	Radiation (reheat) (^oC)
Rawson [3]	0.024	1000	1.20	10	20	730-940
McGraw [12]	0.024	1000	1.225	10	20	---
Fellows and Shaw [13]	0.025	1000	1.280	10	20	720-930

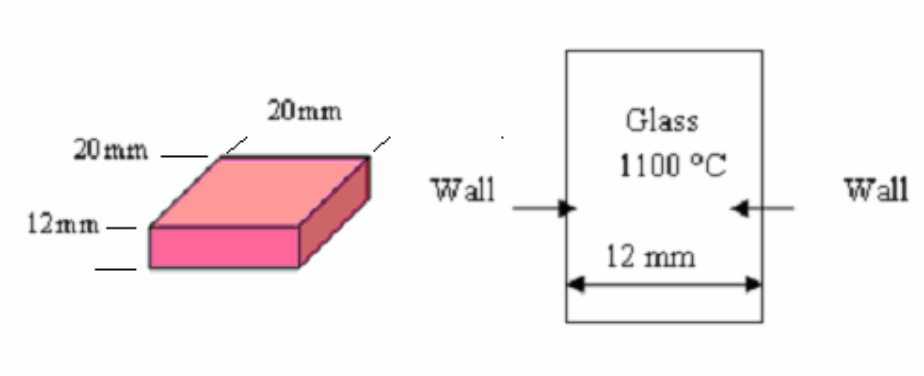

Figure 1: Glass sample dimensions and temperature.

RESULTS

The results obtained by applying each of the four mathematical approaches to the above model are now presented and briefly discussed along with some equivalent experimental results.

Rosseland model cooling of 6 mm soda-lime glass for 50 seconds

Figure (2) shows the result obtained from the model when applying the Rosseland formulation for both the glass surface and centre temperature, over a period of 50 seconds. It can be seen from the figure that the surface and centre temperature range vary from 1100-655°C and 1100-730°C respectively during 50 second period.

A summary of the temperatures at the surface and centre of the glass is given in Table (6) at 10 second intervals. It is clear from the table that as the time increases the temperature difference between the two point's decreases, starting at a maximum difference of 100 °C dropping to a minimum difference of 75 °C at the end of the 50 second period.

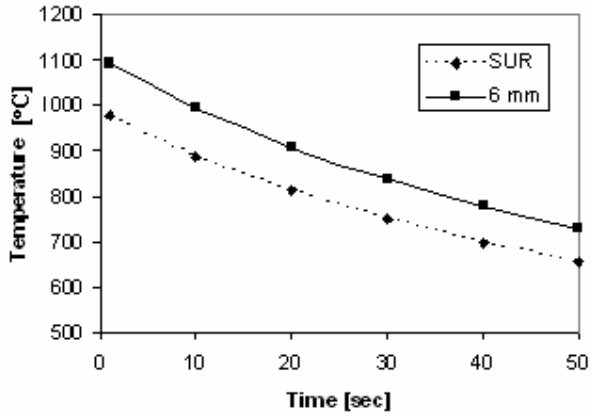

Figure 2: Variations of glass temperature (surface and 6 mm) with time.

Table 6: Surface and centre temperature over 50 seconds cooling (Rosseland)

Time (sec)	1.0	10	20	30	40	50
Temp. (°C) At (6 mm)	1100	995	910	840	780	730
Temp. (°C) At Surface	1000	890	810	750	700	655
Temp. (°C) (Sur.6 mm) Diff.	100	100	100	90	80	75

DTR model cooling of 6 mm soda-lime glass for 50 seconds

Figure (3) shows the results obtained from the DTR model for the glass surface and centre temperatures over a 50 second time period. It can be seen from the figure that the temperatures vary from 1100-655 °C and 1100-730 °C at the surface and centre of the glass over the 50 second period respectively.

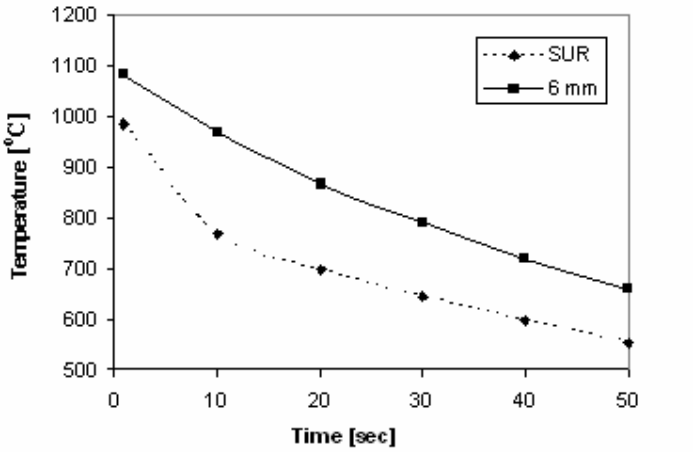

Figure 3: Variations of glass temperature (surface and 6 mm) with time.

A summary of the temperatures at the surface and centre of the glass is given in Table (7) at 10 second intervals. It is clear from the table that as the time increases the temperature difference between the two points decreases, at a maximum difference of 190 °C dropping to a minimum difference of 100 °C at the end of the 50 second period.

Table 7: Surface and centre temperature over 50 seconds cooling (DTR) model

Time (sec)	1.0	10	20	30	40	50
Temp. (°C) At (6 mm)	1100	960	860	790	720	660
Temp. (°C) At Surface	1000	770	700	640	600	560
Temp. (°C) (Sur.6 mm) Diff.	100	190	160	150	120	100

P-1 model cooling of 6 mm soda-lime glass for 50 seconds

Figure (4) shows the results obtained from the P-1 model for the glass surface and centre temperatures over a 50 second time period. It can be seen from the figure that the temperatures vary from 1100-550 °C and 910-610 °C at the surface and at the centre over the 50 second period respectively.

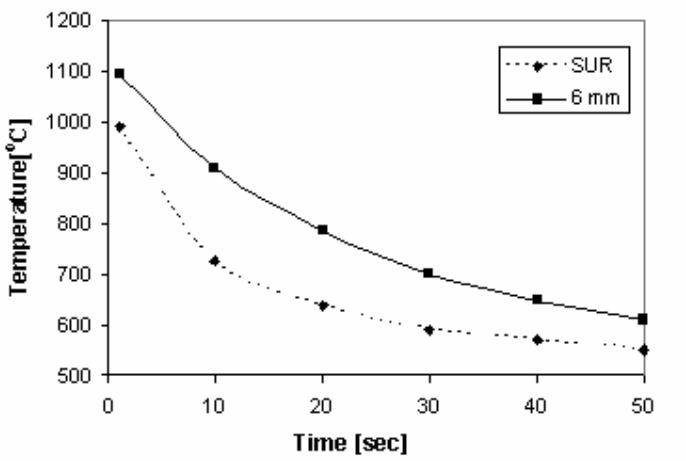

Figure 4: Variations of glass temperature (surface and 6 mm) with time.

A summary of the temperatures at the surface and at the centre of the glass is given in Table (8) at 10 second intervals. It is clear from the table that as the time increases the temperature difference between the two point's decreases, at a maximum difference of 190 °C dropping to a minimum difference of 60 °C at the end of the 50 second period.

Table 8: Surface and centre temperature over 50 seconds cooling (P-1) model

Time (sec)	**1.0**	**10**	**20**	**30**	**40**	**50**
Temp. (°C) At (6 mm)	1100	910	790	700	650	610
Temp. (°C) At Surface	1000	720	630	590	570	550
Temp. (°C) (Sur.6 mm) Diff.	100	190	160	110	80	60

DO model cooling of 6 mm soda-lime glass for 50 seconds

Figure (5) shows the results obtained from the DO model for the glass surface and centre temperatures over a 50 second time period. It can be seen from the figure that the temperatures vary from 1100-500°C and 1100-570°C at the surface and centre of the glass over the 50 second period respectively.

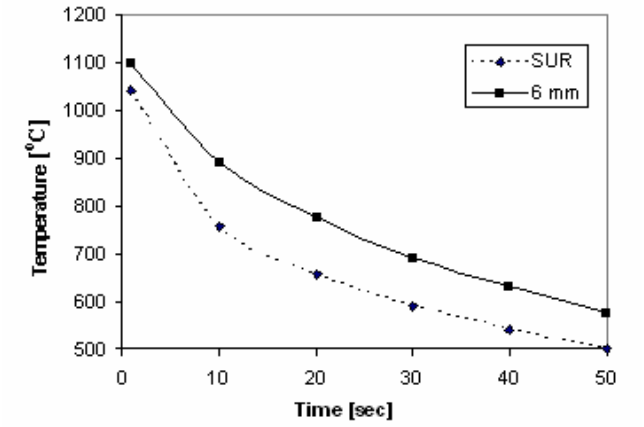

Figure 5: Variations of glass temperature (surface and 6 mm) with time.

A summary of the temperatures at the surface and at the centre of the glass is given in Table (9) at 10 second intervals. It is clear from the table that as the time increases the temperature difference between the two points decreases, at a maximum difference of 130 °C dropping to a minimum difference of 70 °C at the end of the 50 second period.

Table 9: Surface and centre temperature over 50 seconds cooling (DO) model

Time (sec)	**1.0**	**10**	**20**	**30**	**40**	**50**
Temp. (°C) At (6 mm)	1100	890	770	690	630	570
Temp. (°C) At Surface	1050	760	650	590	540	500
Temp. (°C) (Sur.6 mm) Diff.	50	130	120	100	90	70

Experimental results of cooling soda-lime glass of 6 mm for 50 seconds

The experimental work from which the following results were obtained is a piece of 6 mm thick white soda-lime glass is heated to an initial temperature of 1100 °C in a furnace and then removed and cooled in the air at an ambient temperature of 20 ^{o}C for 50 seconds. The glass is placed in an insulating material and is allowed to cool from one surface only, equivalent to the simulations above where the 12 mm thick piece of glass is cooled from two opposite surfaces.

Figure (6) shows how the surface temperature and the temperature at a depth of 6 mm (equivalent to the centre temperature above) change over a 50 second period. The surface temperature drops rapidly, from 1080°C to 515°C in the first 50 seconds and the temperature at a depth of 6 mm drops from 1100 °C to 585°C.

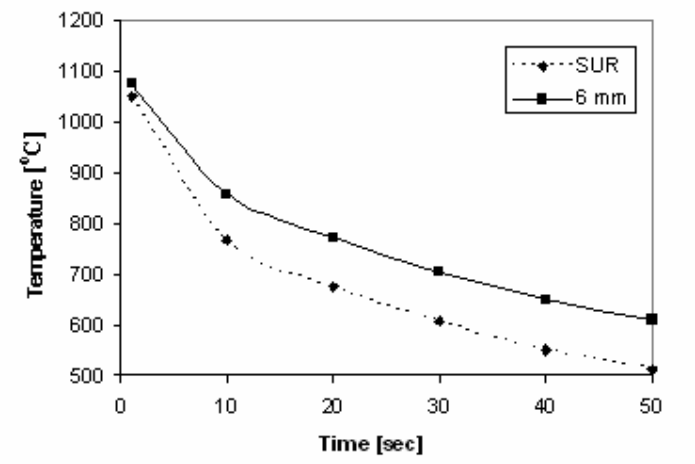

Figure 6: Variations of glass cooling temperature with time.

Table (10) provides a summary of these results and details the numerical difference between the surface and centre (6 mm depth) temperatures at 10 second intervals. The difference between them is at its maximum after 10 seconds with a value of 110 °C, this falls to a minimum value of 70 ^{o}C at the end of the 50 seconds.

Table 10: Experimental results of temperature variation with time

Time (sec)	1.0	10	20	30	40	50
Temp. (°C) At (6 mm)	1100	880	760	690	620	585
Temp. (°C) At Surface	1080	770	660	590	540	515
Temp. (°C) (Sur.6 mm) Diff.	30	110	100	100	80	70

DISCUSSION OF RESULTS

Comparisons of results

Figure (7) shows a comparison of the surface temperatures obtained from the five methods and Tables (11, 12 and 13) provide numerical comparisons. The discussion is separated into two parts; firstly, a comparison between the surface temperatures obtained from the four different mathematical techniques is made and secondly the models are compared with the experimental work presented in Figure (6).

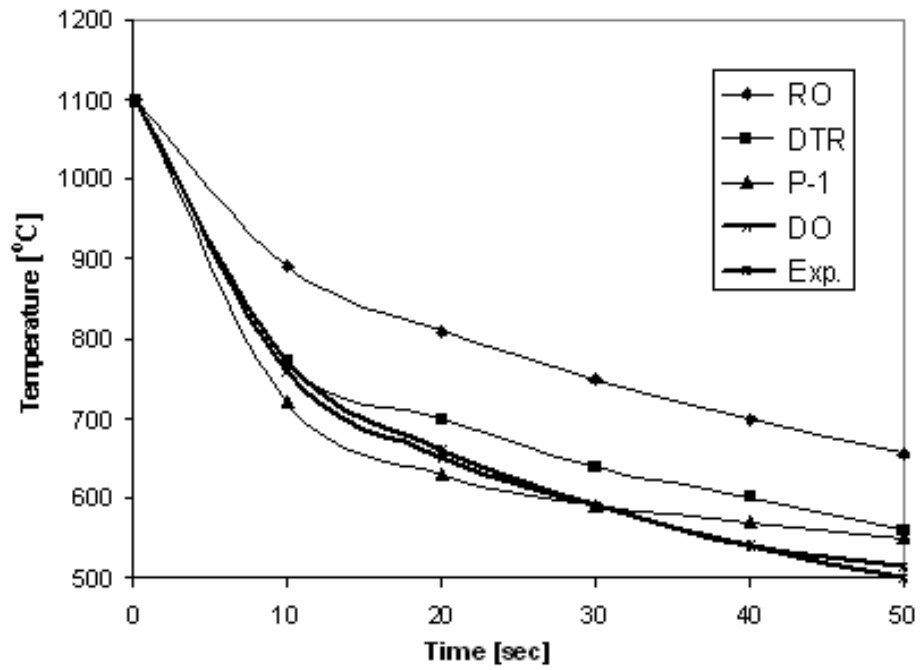

Figure 7: Comparison of models surface temperature with experimental results

Table 11: Comparison of surface temperatures from the four models

Time (sec)	1.0	10	20	30	40	50
Temp. (°C) At Surf. RO	1100	890	810	750	700	655
Temp. (°C) At Surf. DTR	1100	770	700	640	600	560
Temp. (°C) At Surf. P-1	1100	720	630	590	570	550
Temp. (°C) At Surf. DO	1100	760	650	590	540	500
Temp. (°C) At Surf. Exp.	1100	770	660	590	540	515

Table 12: Comparison of temperature differences from models and experiments

Time (sec)	1.0	10	20	30	40	50
Temp. (°C) Diff. RO	100	100	100	90	80	75
Temp. (°C) Diff. DTR	100	190	160	150	120	100
Temp. (°C) Diff.P-1	100	190	160	110	80	60
Temp. (°C) Diff. DO	50	130	120	100	90	70
Temp. (°C) Diff. Exp.	30	110	100	100	80	70

Comparison of modelling results

Comparing the results obtained from the four models, given in Table (11), it is clear that over the 50 second cooling period Rosseland model predicts the smallest surface temperature drop, from 1100°C to 655°C, while DO predicts the largest, from 1100°C to 500°C, a difference of over 145 °C. The other two models predict almost equal surface temperature falls to around the 550 °C. The profile of the temperature decayed exponentially in all cases, with the DTR, P-1 and DO models showing the same general trend while the Rosseland model predicts far slower heat loss. The DO model predicts the fastest heat loss.

The centre temperatures predicted by the four models over the 50 second cooling period, given in Table (11), show the same trends as the surface temperature, with Rosseland showing the smallest heat loss while DO shows the highest. This should be expected as the DO model formulation allows a greater dissipation of energy from the surface.

For clarification, the difference between the centre and surface temperatures are compared in Table (12). This shows that the temperature predicted in the DTR and P-1 models are much greater than in the Rosseland and DO models, reaching a temperature after the first 10 seconds of 190 °C in comparison to the DO model at 130 °C. After the initial rise in temperature over the first 10 seconds it steadily decreases as the rate at which heat is transferred from the centre to the surface approaches that being lost by the surface to the air. The DTR model maintains the highest temperature level after 50 seconds of 100 °C, while the P-1 model decreases the temperature gradient most rapidly down to 60 °C from the maximum 190 °C.

Comparison of modelling and experimental results

In order to provide some evidence as to which model best predicts the actual heat transfer in the experimental work has been performed, which is discussed in pervious section. The experimental results are shown along with the modelling results in Figure (7), and Tables (11, 12). It is clear from both the graph of surface temperature and the numerical results given in the tables that the DO model offers the closest prediction to the practical measurements and it is noticeable that as time increases the DO model converges towards the experimental result.

It has been suggested in the literature (Cheong and Song [15] and Viskanta and Song [2]) that the DO model would provide the best approximation to the real world and that this is mainly due to the optical thickness and its effect on the assumptions used in the derivation of the other mathematical models.

CONCLUSIONS

In this work the modelling of heat transfer from a soda-lime glass surface by radiation has been studied. Four different mathematical techniques have been applied to the same model and the results obtained from each method have been compared with experimental work to show which provides the best estimation to the actual result. The model considered the radiative heat loss from glass to air over a 50 second period and this model was mirrored in the experimental work. The temperature of the glass was recorded at the glass surface and at the centre of the glass.

The comparison of the modelling results and the experimental results in Figure (7) and Tables (11–12) shows that the DO modelling method provides the closest result to that obtained experimentally. The DTR and P-1 modelling techniques offer reasonable approximations over the 50 second period observed for the most part within a 10% error. However, the Rosseland model is unable to provide a good prediction; it shows heat being lost from the glass too slowly. This has been discussed as resulting from the optical thickness of the glass being too small for the approximations made in the Rosseland formulation.

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