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Periodic Analysis of the Cooling Temperature of Al-Si-Mg Alloy Cast Based on Its Thickness and Cooling Time

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Abstract

This paper presents a periodic empirical analysis of the cooling temperature of Al-Si-Mg alloy cast based on its thickness and cooling time during the cooling process. A two-factorial model was derived, validated and used for the analysis. The derived model showed that the cooling temperature of the Al-Si-Mg alloy cast is a linear function of its thickness and cooling time. The validity of the derived model expressed as: $\xi = -11.09 + 0.0001\tau + 782$ was rooted on the model core expression $\xi - 0.0001\tau = -11.09 + 782$ where both sides of the expression are correspondingly approximately equal. Results from evaluations indicated that the standard error incurred in predicting the cooling temperature of Al-Si-Mg alloy cast for each value of its thickness & cooling time considered, as obtained from experiment and derived model were 20.16 and 0% & 33.67 and 14.85 % respectively. The cooling temperature of Al-Si-Mg alloy cast per unit thickness & cooling time as obtained from experiment and derived model results are 11.43 and 11.0 °C /mm & 0.72 and 0.69 °C / s, respectively and the correlations with thickness & cooling time were all > 0.9. Maximum deviation of model-predicted cooling temperature of Al-Si-Mg alloy cast from the experimental results is 3.38%. These invariably translated into over 96% operational confidence for the derived model as well as over 0.96 reliability response coefficients of Al-Si-Mg alloy cast cooling temperature to its thickness & cooling time.

Keywords: Periodic analysis, Cooling temperature, Al-Si-Mg alloy cast, Thickness, Cooling time.

1. Introduction

The need for controlled cooling of metal and alloy cast during solidification has raised the need for intensive research and development geared towards unraveling better methods of ensuring uniform cooling throughout the cast in order to decentralize associated stress.

It has been posited ^[1] that cooling curves are temperature time dependent relation obtained during modification of metal or/an alloy in the mould. The researcher concluded that cooling curves are powerful tool used to study transformations occurring during the solidification process.

Report ^[2] has shown that the cooling rate may be obtained at any temperature from temperature-time cooling curve by drawing a tangent to the curve at the temperature and determining the value of slope for the tangent. The cooling rate has been revealed ^[3] to be controlled by a number of resistances to heat flow. Some of the resistances to heat flow from the system through the casting to the surrounding are (1) the liquid (2) the solidified metal (3) the metal/ mould interface (4) the mould (5) the surrounding of the mould.

Heat transfer and (invariably loss) from a solidifying cast has been found to be dominated by conduction ^[4]. The researcher maintained that conduction is the mechanism in which the heat is transferred internally within the solidifying metal and the mould. Earlier report ^[5] revealed that convection involves the movement of the liquid metal during casting under the driving force of the density differences in the liquid. The scientist also submitted that it is a transport phenomenon where particles are carried by the fluid over some distances.

Other researchers ^[6] have cited the existence of convection as important because it affects the columnar to equiaxed transition. Similar work ^[7] has reported that convection driven by solutes can raise a number of problems for example heavy solutes cause the liquid to sink, and higher solutes cause floatation.

The present work aims at carrying out a periodic analysis of the cooling temperature of Al-Si-Mg alloy cast based on its thickness and cooling time during the solidification process.

2. Materials and method

The materials used for this research work includes aluminium scrap of 92.6% Al by composition (from First Aluminium Port Harcourt), silicon obtained from Metallurgical Training Institute, Onitsha, and Magnesium (in form lumps) obtained from Bridge Head Market Onitsha, Anambra state. The details of experiments carried out and the prevailing conditions are as stated in the report [8].

3. Results and Discussions

Table 1 show that the cooling temperature of Al-Si-Mg alloy cast is linearly dependent on its thickness and cooling time following pouring of melt into a mould of initial temperature of 28°C.

Table 1: Variation of cooling temperature of Al-Si-Mg alloy cast with its thickness and cooling time [8]

θ	(ϑ)	(ξ)
11	5	750
58	10	650
211	20	550
374	30	450
565	40	350

3.1 Model formulation

Computational analysis (using C-NIKBRAN: [9]) of results in Table 1 indicates that

$$\xi - K\gamma = -N\vartheta + S \tag{1}$$

Substituting the values of K, N and S into equation (2) reduces it to;

$$\xi - 0.0001\gamma = -11.09 + 782 \tag{2}$$

$$\xi = -11.0\vartheta + 0.0001\gamma + 782 \tag{3}$$

Where

K = 0.0001; N = 11.0 and S = 782 are equalizing constants (Determined using C-NIKBRAN [9])

(ξ) = Cooling temperature (°C)

(ϑ) = Thickness (mm)

(γ) = Cooling time (s)

3.1.1 Boundary and Initial Conditions

Considered ranges of cooling temperature, cooling time and Al-Si-Mg alloy cast thickness as 350-750°C, 11-565s and 5 – 40mm respectively. The initial mould temperature was maintained at 28°C.

3.1.2 Model validation

Table 2: Variation of ξ - 0.0001γ with - 11.09 + 782

ξ - 0.0001γ	- 11.09 + 782
749.9989	727.0
649.9942	672.0
549.9789	562.0
449.9626	452.0
349.9435	342.0

The validity of the derived model was rooted in equation (2) where both sides of the equation are correspondingly approximately almost equal. Furthermore, equation (2) agrees with Table 2 following the values of ξ - 0.0001γ and - 11.09 + 782 evaluated from Table 1.

Furthermore, the derived model was validated by comparing the model-predicted cooling temperature of Al-Si-Mg alloy cast and that obtained from the experiment. This was done using the 4th Degree Model Validity Test Techniques (4thDMVTT); statistical graphical, computational and deviational analysis.

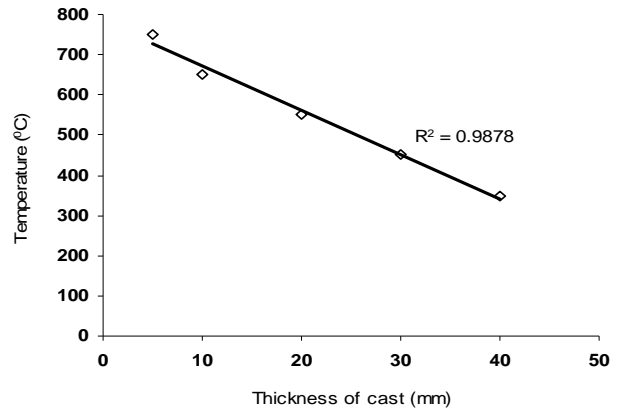


Fig 1: Variation of Al-Si-Mg alloy cast cooling temperature with its thickness as obtained from experiment [8]

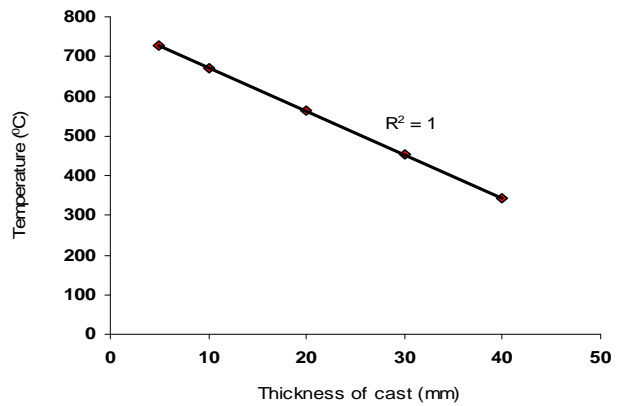


Fig. 2: Variation of Al-Si-Mg alloy cast cooling temperature with its thickness as predicted by derived model

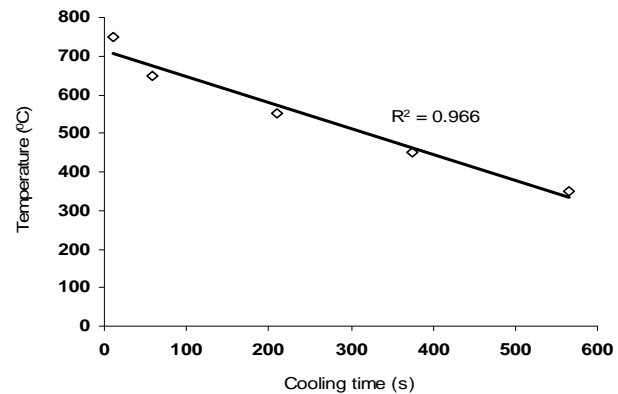


Fig. 3: Variation of Al-Si-Mg alloy cast cooling temperature with its cooling time as obtained from experiment [8]

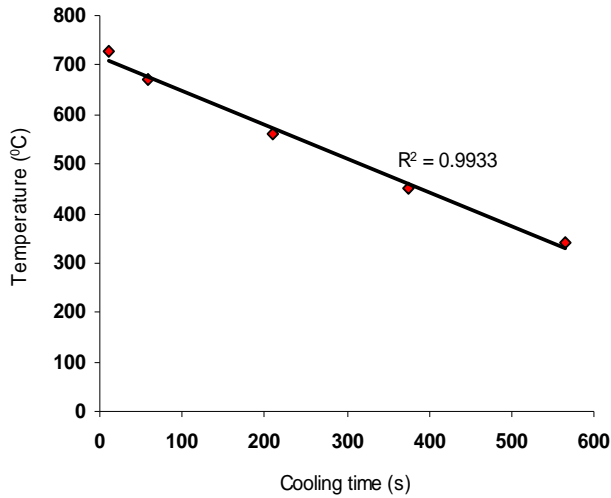


Fig. 4: Variation of Al-Si-Mg alloy cast cooling temperature with its cooling time as predicted by derived model.

3.2 Statistical Analysis

3.2.1 Standard Error (STEYX)

The standard errors incurred in predicting the cooling temperature of Al-Si-Mg alloy cast for each value of the thickness & cooling time considered as obtained from experiment and derived model were 20.16 and 0% & 33.67 and 14.85 % respectively. The standard error was evaluated using Microsoft Excel version 2003.

3.2.2 Correlation (CORREL)

The correlation coefficient between cooling temperature of Al-Si-Mg alloy cast and thickness & cooling time were evaluated (using Microsoft Excel Version 2003) from results of the experiment and derived model. These evaluations were based on the coefficients of determination R^2 shown in Figs. 1- 4.

$$R = \sqrt{R^2} \quad (4)$$

The evaluated correlations are shown in Tables 3 and 4. These evaluated results indicate that the derived model predictions are significantly reliable and hence valid considering its proximate agreement with results from actual experiment.

Table 3: Comparison of the correlations evaluated from derived model predicted and experimental results based on thickness

Analysis	Based on thickness	
	ExD	D-Model
CORREL	0.9939	1.0000

Table 4: Comparison of the correlations evaluated from derived model predicted and experimental results based on cooling time

Analysis	Based on cooling time	
	ExD	D-Model
CORREL	0.9829	0.9966

3.3 Graphical Analysis

Comparative graphical analysis of Figs. 5 and 6 show very close alignment of the curves from the experimental (ExD) and model-predicted (MoD) cooling temperature of Al-Si-Mg alloy cast.

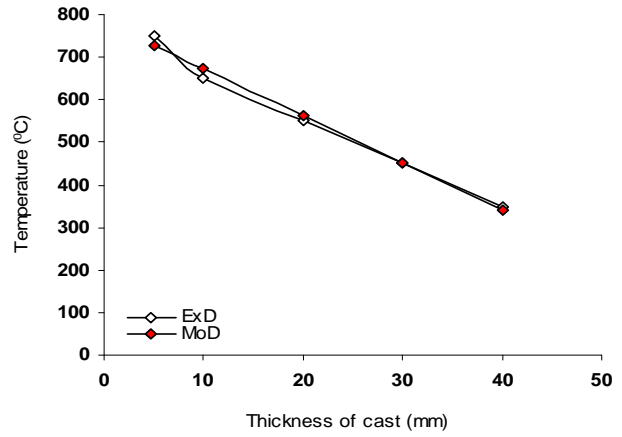


Fig. 5: Comparison of cooling temperatures of Al-Si-Mg alloy cast (relative to the cast thickness) as obtained from experiment [8] and derived model.

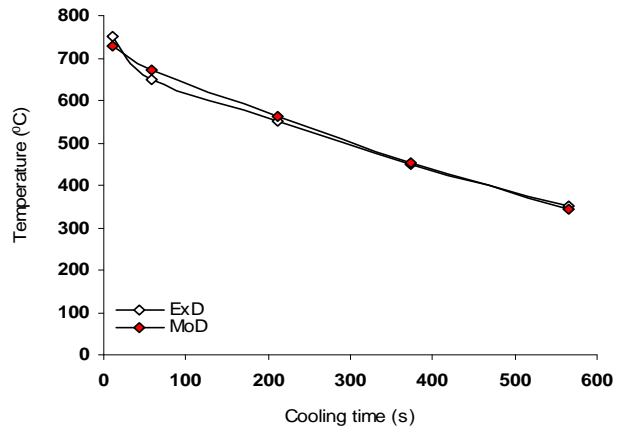


Fig.6: Comparison of cooling temperatures of Al-Si-Mg alloy cast (relative to the cast cooling time) as obtained from experiment [8] and derived model.

It is strongly believed that the degree of alignment of these curves is indicative of the proximate agreement between both experimental and model-predicted cooling temperatures of the Al-Si-Mg alloy cast.

3.4 Computational Analysis

Computational analysis of the experimental and model-predicted cooling temperatures of Al-Si-Mg alloy cast was carried out to ascertain the degree of validity of the derived model. This was done by comparing the cooling temperature of Al-Si-Mg alloy cast per unit thickness and per unit cooling time obtained from evaluation of experimental and model-predicted results.

3.4.1 Al-Si-Mg alloy cast cooling temperature per unit thickness

The Al-Si-Mg alloy cast cooling temperature per unit thickness was calculated from the expression;

$$\xi_t = \Delta \xi / \Delta \vartheta \quad (5)$$

Equation (5) is detailed as

$$\xi_t = \xi_2 - \xi_1 / \vartheta_2 - \vartheta_1 \quad (6)$$

$$\xi_t = \xi_2 - \xi_1 / \varpi_2 - \varpi_1 \quad (7)$$

Where

$\Delta \xi$ = Change in the alloy cooling temperature at two cooling times and thickness values ϖ_1 , ϖ_2 , and ϑ_2 , ϑ_1 respectively.

Considering the points (5, 750) & (40, 350) and (5, 727) & (40,342) as shown in Fig. 5, then designating them as (ζ_1, ϑ_1) & (ζ_2, ϑ_2) for experimental and model predicted results respectively, and also substituting them into equation (6), gives the slopes: 11.43 and 11.0 °C/ mm as their respective cooling temperature of Al-Si-Mg alloy cast per unit thickness.

3.4.1.1 Al-Si-Mg alloy cast cooling temperature per unit cooling time

Also considering the points (11, 750) & (565, 350) and (11, 727) & (565,342) as shown in Fig. 6, then designating them as (ζ_1, τ_1) & (ζ_2, τ_2) for experimental and model predicted results respectively, and also substituting them into equation (7), gives the slopes: 0.72 and 0.69 °C/ s as their respective cooling temperature of Al-Si-Mg alloy cast per unit cooling time.

3.5 Deviation Analysis

Critical analysis of the Al-Si-Mg alloy cast cooling temperature obtained from experiment and derived model show deviations on the part of the model-predicted values relative to values obtained from the experiment. This was attributed to the fact that the surface properties of the alloy cast and also the physico-chemical interactions between the matrix and alloying elements which played vital roles during processing were not considered during the model formulation. This necessitated the introduction of correction factor, to bring the model-predicted Al-Si-Mg alloys cast cooling temperature to those of the corresponding experimental values.

The deviation Dv , of model-predicted Al-Si-Mg alloy cast cooling temperature (from the corresponding experimental result) is given by

$$Dv = \xi_{MoD} - \left(\frac{\xi_{ExD}}{\xi_{ExD}} \times 100 \right) \quad (8)$$

Where

ξ_{ExD} and ξ_{MoD} are Al-Si-Mg alloy cast cooling temperatures obtained from experiment and derived model respectively.

Deviational analysis of Figs. 9 and 10 indicate that the precise maximum deviation of model-predicted Al-Si-Mg alloy cast cooling temperature from the experimental results is 3.38%. This invariably translated into over 96% operational confidence for the derived model as well as over 0.96 reliability response coefficients of Al-Si-Mg alloy cast to its thickness & cooling time.

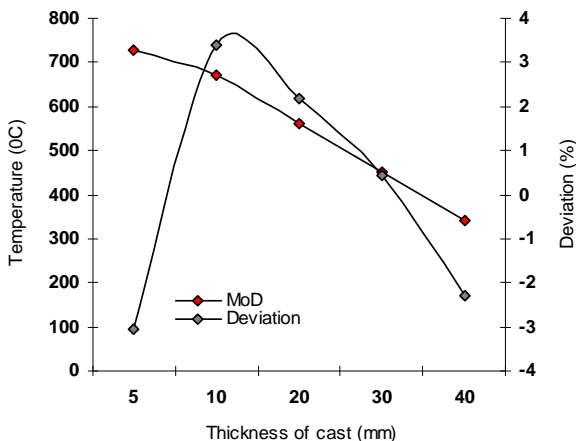


Fig. 9: Variation of model-predicted cooling temperature of Al-Si-Mg alloy cast (relative to thickness) with associated deviation from experiment.

Consideration of equation (8) and critical analysis of Figs. 9 and 10 show that the least and highest magnitudes of deviation of the model-predicted cooling temperature of Al-Si-Mg alloy cast (from the corresponding experimental values) are + 0.44 and + 3.38%. Figs. 9 and 10 indicate that these deviations correspond to Al-Si-Mg alloy cast cooling temperatures: 452 and 672°C, thicknesses: 30 and 10 mm as well as cooling times: 374 and 58 s respectively.

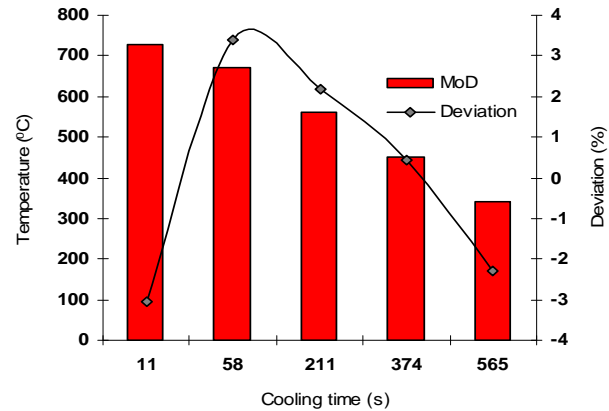


Fig. 10: Variation of model-predicted cooling temperature of Al-Si-Mg alloy cast (relative to cooling time) with associated deviation from experiment.

Correction factor, Cf to the model-predicted results is given by

$$Cf = - \left(\frac{\xi_{MoD} - \xi_{ExD}}{\xi_{ExD}} \right) \times 100 \quad (9)$$

Critical analysis of Figs. 9, 10 and Table 5 indicates that the evaluated correction factors are negative of the deviation as shown in equations (8) and (9).

Table 5: Variation of correction factor (to model-predicted cooling temperature of Al-Si-Mg alloy cast) with thickness and cooling time

(y)	(9)	Correction factor (%)
11	5	- 3.07
58	10	+ 3.38
211	20	+ 2.18
374	30	+ 0.44
565	40	- 2.29

Table 5 shows that the least and highest correction factor (to the model-predicted cooling temperature of Al-Si-Mg alloy cast) are - 0.44 and - 3.38%. Since correction factor is the negative of deviation as shown in equations (8) and (9), Table 5, Figs. 9 and 10 indicate that these highlighted correction factors correspond to Al-Si-Mg alloy cast cooling temperatures: 452 and 672°C, thicknesses: 30 and 10 mm as well as cooling times: 374 and 58 s respectively.

The correction factor took care of the negligence of operational contributions of the surface properties of the alloy cast and also the physico-chemical interactions between the matrix and alloying elements which actually played vital role during the cooling process. The model predicted results deviated from those of the experiment because these contributions were not considered during the model formulation. Introduction of the corresponding values of Cf from equation (9) into the model gives exactly the corresponding experimental values of the Al-Si-Mg alloy cast cooling temperature.

It is very pertinent to state that the deviation of model predicted results from that of the experiment is just the magnitude of the value. The associated sign preceding the value signifies that the deviation is a deficit (negative sign) or surplus (positive sign).

4. Conclusion

Periodic empirical analysis of the cooling temperature of Al-Si-Mg alloy cast was carried out based on its thickness and cooling time during the cooling process. A two-factorial model derived and validated was used for the analysis. The cooling temperature of the Al-Si-Mg alloy cast was a linear function of its thickness and cooling time. The validity of the derived model was rooted on the model core expression $\xi - 0.0001x = -11.09 + 782$ where both sides of the expression are correspondingly approximately equal. Results from evaluations indicated that the standard error incurred in predicting the cooling temperature of Al-Si-Mg alloy cast for each value of its thickness & cooling time considered, as obtained from experiment and derived model were 20.16 and 0% & and 33.67 and 14.85 % respectively. The cooling temperature of Al-Si-Mg alloy cast per unit thickness & cooling time as obtained from experiment and derived model results are 11.43 and 11.0 °C /mm & 0.72 and 0.69 °C / s, respectively and the correlations with thickness & cooling time were all > 0.9. Maximum deviation of model-predicted cooling temperature of Al-Si-Mg alloy cast from the experimental results is 3.38%. These invariably translated into over 96% operational confidence for the derived model as well as over 0.96 reliability response coefficients of Al-Si-Mg alloy cast to its thickness & cooling time.

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