Development of Finite Element Model for the Control of Solidification Shrinkage in Al-Si (A8011) Alloy Castings

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Abstract- The objective of this research work is to determine a realistic way of minimizing shrinkage in Aluminium-Silicon (Al-Si) alloy castings using finite element modelling. Finite Element method was used to discretize and solve the governing equations developed for the models using the commercial software, Comsol Multi-Physics. The models developed were validated from experimental data obtained from the foundry using six samples which were used to study the temperature profiles and nature of the solidification of the alloys. A comparison of the temperature profiles generated from the experiments and simulations show that in 64% of the processes, there were no significant differences between the experimental and simulated values. In comparing the Niyama values obtained from the experiments and those from the simulations, there were no significant differences in 46% of the processes. Threshold Niyama values of 0.143 (°C-s)\(^{1/2}\)mm was also established. Below these threshold values, it is predicted that shrinkage will occur in castings from these metals.

Keywords- Aluminium alloy, Al-Si (A8011), Castings, Finite Element, Shrinkage, Solidification.

1INTRODUCTION

It is widely reported that the final structure of a cast therefore depends on its solidification history (Voller, 1998; Nikanorov et al., 2005). This eventually indicates that the properties of castings are directly related to the final structures developed after the casting (Sinha & Goel, 1978). Thus, to produce sound castings, it is important to understand the process of solidification of castings and various variables that may cause defects during solidification. Beeley (2001) concluded that properties and service performance of an individual casting are a function of its soundness, that is, the degree of true metallic continuity which is established during solidification. In this regard too, it suffices to note that as pointed out by Akpobi & Lawani (2006), the nature of cooling in a casting determines the quality of casting. In their view, they stated that in designing a part to be cast, use of experimental methods to study the characteristics of the final products is expensive hence the reason for the use of numerical simulations during the design stages. It must also be pointed out that modern day foundry men now appreciate the benefits of solidification modelling in the control of their processes (Overfelt, 1992).

Ye (2003) stated that Al-Si binary alloy is a eutectic system with the eutectic composition at 12.6 wt % Si. Silicon reduces the thermal expansion coefficient, increases corrosion and wear resistance, and improves casting and machining characteristics of the alloy. Pure aluminium possesses relatively poor casting characteristics and therefore castings are produced from aluminium alloys (Khanna, 1996). Jumroonrut & Pitakthanapaph (2005) worked on the filling and solidification simulation of Aluminium casting process. The work investigated the casting of Aluminium by finite difference simulation. A model representing an automotive part was developed. The Aluminium used was the cast Aluminium (A355) at the pouring temperature of 700 °C.

The mould which was made of white iron was heated and kept at 350°C. The filling time was approximately 7 seconds for the different gating designs. It was found that the design of the gating system has strong effects on the filling behaviour of the molten Aluminium and the solidification process, hence quality of the cast product. By using riser, the undesirable defects such as shrinkage can be controlled, leaving the cast defect free and maintaining its strength. FEM is an efficient design tool for performing parametric design studies by considering various design cases (different shapes, materials, loads, boundary conditions and analyzing them, and choosing the optimum design (Zeid, 2005).

Zeid (2005) said finite element analysis begins by approximating the continuum under study by assemblage of discrete finite elements. The elements are interconnected at the nodal points (nodes) on the element boundaries. Most finite elements are geometrically simple to meet the fundamental premise of the finite element method that a continuum of an arbitrary shape can be accurately modelled by an assemblage of elements. For 1-d elements, there is one independent variable and elements are line segments. The number of nodes per element depends on the nodal variables (degree of freedom) and the continuity requirements between the elements (Cailletaud & El-Arem, 2001; De-Weck & Kim, 2004).

Akpobi & Lawani (2006) did a two-dimensional finite element simulation of cooling in castings. A one way coupling technique was used to predict the behaviour of thermal strains and stresses from the temperature history of casting. The temperature distribution across the casting at different times, the cooling pattern of the casting in different cooling media, the cooling times and the build-up of thermal strains and stresses were simulated. Droux (1989) stated that various numerical methods can be applied to the simulation of solidification. Overfelt (1992) said the implementation of solidification kinetics requires a balanced program of experimental data coupled with

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computer simulations of heat transfer, nucleation and growth processes.

2. MATERIALS AND METHOD
This study involved finite element modeling and software development for the control of solidification shrinkage in aluminum-silicon alloys. The finite element models were developed using the commercial software, Comsol Multi-physics obtained with assistance from the National Agency for Science and Engineering Infrastructure, Abuja, Nigeria while the practical work for the validation of the developed models was carried out at the Engineering Materials Development Institute, Akure, Ondo State, Nigeria (EMDI).

2.1 MATERIAL PROPERTIES FOR ALUMINIUM ALLOY A8011
The following relevant thermal properties were provided by Tower Aluminium Rolling Mills, Ota, Ogun State, Nigeria. These values were used for the simulation and foundry experiments (Table 1).

| % Composition | Melting Point (°C) | Specific Heat (J/KG.K) | Thermal Conductivity (W/M.K) | Thermal Expansivity (µstrain/°C) | Density (Kg/M³) |
|--------------|-------------------|------------------------|-------------------------------|-------------------------------|----------------|
| Al           | 98.34             | 510                    | 980                           | 81                            | 21.3           | 2890           |
| Si           | 0.47              |                        |                               |                               |                |

2.2 PREPARATION OF THE TEST PIECES
Green sand casting was used to produce 6 test pieces for Aluminium alloy A8011. The dimensions of the test pieces are shown in Table 2. The castings were careful produced based on conditions and parameters to facilitate directional solidification. During casting, when the solidification progresses to the innermost region or hot spots, a lack of liquid metal leads to voids called shrinkage cavities. In these experiments, the gating and feeding systems were designed to ensure that the Risers solidify later that the hot spots. Also, the necessary shrinkage allowances were taken into consideration in constructing the patterns for the castings. Figure 1 shows Alloy 8011 plates before melting.

| Casting Size (mm) | Down Sprue (mm) | Riser (mm) | Ingate (mm) | Runner Bar (mm) | Vent (mm) |
|-------------------|-----------------|------------|-------------|-----------------|-----------|
| 200 × Ø50         | 70 × Ø25        | 70 × Ø20   | 30 ×69 × 17 (2 no) | 0              | 70 × Ø 5 (2 no) |
| 150 × Ø50         | 70 × Ø25        | 70 × Ø20   | 30 ×69 × 17 (2 no) | 0              | 70 × Ø 5 (2 no) |
| 200 × Ø25         | 70 × Ø20        | 70 × Ø10   | 30 ×42 × 7 (2 no) | 0              | 70 × Ø 5 (2 no) |

Table 2. Dimensions of test pieces and their gating systems

| Casting Size (mm) | Down Sprue (mm) | Riser (mm) | Ingate (mm) | Runner Bar (mm) | Vent (mm) |
|-------------------|-----------------|------------|-------------|-----------------|-----------|
| 200 × 50 × 39.4   | 70 × Ø25        | 70 × Ø25 (2 nos) | 24 ×42 × 7 (2 no) | 150 × 25 × 20 | 70 × Ø 5 (2 nos) |
| 150 × 50 × 39.4   | 70 × Ø25        | 70 × Ø20   | 30 ×69 × 17 (2 no) | 70 × Ø 5 (2 nos) |
| 200 × 25 × 19.4   | 70 × Ø20        | 70 × Ø10   | 24 ×42 × 7 (2 no) | 70 × Ø 5 (2 nos) |
2.3 MOULD PREPARATION
The moulds were prepared from green sand with Bentonite as binder. Properties of the moulding sand include permeability value of 150 cmWH, green strength of 78.4 KN/m\(^2\) and moisture meter of 3.0%. Figure 4 shows one of the prepared moulds for cylindrical shapes and rectangular shapes respectively.

![Fig. 4: Prepared mould for (a) rectangular samples (b) cylindrical samples](image)

2.4 CRITERION FOR PREDICTION OF SHRINKAGE
Table 3 shows the existing thermal criteria for prediction of shrinkage as proposed in literatures (Mina (2005). It provides a less complex way of predicting shrinkage in castings. The Niyama criterion is given by Eqn. 1:

\[
G = \frac{G}{V_s} \sqrt{R_t s_m V_s n}
\]

Where \(G\) is the thermal gradient given by:

\[
G_{ij} = \frac{(T_j - T_i)\, D_s}{s_m V_s n}
\]

Where \((T_j - T_i)\) is the difference in temperature between two points \(i\) and \(j\) in the casting and \(D_s\) is the distance between these points.

\[
R_t = \frac{(T_j - T_i)}{(\tau_2 - \tau_1)}
\]

Bailey et al (1997) stated that if \(G_{ij}/R_t\) is less than 1, there is a high possibility of shrinkage occurring in Steel castings.

| Table 3. Existing Thermal Criteria for Prediction |
|-----------------------------------------------|
| Criterion          | Author            | Year Proposed |
| \(\frac{G}{V_s}\) | Bishop et al      | 1951          |
| \(\frac{1}{V_s}n\) | Davies            | 1975          |
| \(\frac{G}{V_s}\) | Khan              | 1980          |
| \(\frac{G}{V_s}\) | Niyama et al.     | 1982          |
| \(\frac{G}{V_s}\) | Lacome-Beckers    | 1988          |
| \(\frac{G_{0.33}}{V_s}\) | Lee et al.       | 1990          |
| \(\frac{G_{0.38}}{V_s}\) | Kao et al        | 1994          |
| \(1/t_{sm}V_s n\) | Chiesa           | 1998          |

Source: Mina (2005)

The Niyama criterion which is the most popular and frequently used of all the criteria was adapted for the prediction of shrinkage. It was chosen because it

\[
\frac{G_{ij}}{R_t} < 1
\]

Where \(G\) is the thermal gradient given by:

\[
G_{ij} = \frac{(T_j - T_i)\, D_s}{s_m V_s n}
\]

Where \((T_j - T_i)\) is the difference in temperature between two points \(i\) and \(j\) in the casting and \(D_s\) is the distance between these points.

\[
R_t = \frac{(T_j - T_i)}{(\tau_2 - \tau_1)}
\]

\[
R_{et}, \text{ the rate of cooling rate from an instant of time } \tau_1 \text{ to } \tau_2 \text{ at a given location inside the casting is given by Eqn. 3:}
\]

\[
R_{et} = \frac{(T_j - T_i)}{(\tau_2 - \tau_1)}
\]

2.5 FINITE ELEMENT MODEL DEVELOPMENT FOR MOULD FILLING AND SOLIDIFICATION
Sequential steps were followed in the development of the solidification model. The commercial software, Comsol Multi-Physics was used to generate the nodes, element matrices and compute nodal values and derivatives. The same software was used to carry out analysis and compute the final solidification time, fraction of solid, temperature gradient, cooling rate, pressure, temperature and liquid metal velocity.
2.6 TEMPERATURE MEASUREMENT
Two K-type thermocouples probes, 25mm apart were inserted into each of the moulds. The thermocouples were then connected to digital multi-meters from where temperature readings were taken at 20s intervals with a stop clock.

2.7 MELTING OF THE ALLOY SPECIMENS AND POURING
The alloy specimens were melted in a diesel fired crucible furnace and the pouring temperatures were read off from an optical pyrometer.

2.8 DISCRETIZATION OF NUMERICAL MODEL
The coupled equations for solidification in shrinkage flow was adopted and solved using the commercial software, Comsol Multi-physics. Two shapes, rectangular and cylindrical were used in the simulation. The choice of the two shapes was to reduce the complexity of the equations to be solved. Also, the cost of validating the models experimentally for three shapes was taken into consideration. Three sizes were simulated (Table 1) for each of the shapes. In all, six different geometries were developed and discretized for the simulations.

3 RESULTS AND DISCUSSION
Finite Element Analysis was carried out using data from six samples for a better insight into the temperature profiles and nature of the solidification of the alloys. The models developed were validated using experimental data. From the Finite Element Analysis, a helpful insight has been given to the nature of liquid metal velocity during mould filling, pressure contours that develop during solidification and temperature distribution as the metal cools. In all six samples of different dimensions (3 for cylindrical shapes and 3 rectangular shapes) were analysed. Data generated included temperature readings using Probes 1 and 2, for both experimental and simulated. Other data generated are experimental thermal gradients, experimental cooling rates, Niyama experimental and simulated values, while the time of readings varied from 20 - 480 seconds. Some of the data generated are presented. Appendix A shows the readings for Alloy A8011 cylindrical shape sample 1 while the graphs (Figures 5 & 6) represented experimental and simulation results.

Figures 7 & 8 show the replacement of samples of the twelve shapes by a set of nodes to produce tetrahedral and triangular elements using Comsol Multi-Physics. The details of the elements generated are shown in Table 4. The collection of nodes and elements forms the finite element mesh.
Table 4. Meshing and Discretization Data from Comsol Multi-Physics

| Alloy                   | Tetrahedral Elements | Triangular Elements | Meshing Volume | Average Element Quality | Average Growth Rate |
|-------------------------|----------------------|---------------------|----------------|-------------------------|---------------------|
| A8011 (Rectangular 1)   | 1619                 | 1086                | 6.051e-4m³     | 0.5584                  | 2.125               |
| A8011 (Rectangular 2)   | 1231                 | 812                 | 4.171e-4m³     | 0.6264                  | 1.842               |
| A8011 (Rectangular 3)   | 1920                 | 1030                | 1.365e-4m³     | 0.6001                  | 2.071               |
| A8011 (Cylinder1)       | 1615                 | 872                 | 4.973e-4m³     | 0.6956                  | 1.569               |
| A8011 (Cylinder2)       | 1655                 | 910                 | 4.038e-4m³     | 0.6944                  | 1.657               |
| A8011 (Cylinder3)       | 2783                 | 1292                | 1.314e-4m³     | 0.6986                  | 1.699               |
| A8011 (Rectangular 1)   | 1619                 | 1086                | 6.051e-4m³     | 0.5584                  | 2.125               |
| A8011 (Rectangular 2)   | 1231                 | 812                 | 4.171e-4m³     | 0.6264                  | 1.842               |
| A8011 (Rectangular 3)   | 1920                 | 1030                | 1.365e-4m³     | 0.6001                  | 2.071               |

Fig. 8 Rectangular 1: Discretization Meshing

Appendix B was the readings for Alloy A8011 rectangular shape (200mm × 50mm × 39.3mm) with the graphs (Figures 9 & 10) both represented experimental and simulation temperatures results. For probes 1 & 2, and simulated Niyama values. For a cylindrical shape with Ø50mm × 200mm dimension.

Outputs from Finite Element Simulations using Comsol Multi-Physics: Figure 11 represents a section velocity of the melt showing the motion of the melt 840s after pouring. 3D view of simulated casting is shown in Figure 12. These indicate that the metal has cooled to about 400 °C except for the sprue area. The low liquid fraction shows that the metal is completely solidified except for the sprue where there exists a high liquid fraction.

Fig. 9: Probes 1&2 Temperature Profile for Alloy A8011 (Cylinder 2)

Fig. 10: Graph of the Niyama Criteria for Alloy A8011 (Cylinder 2)

Fig. 11: Cylinder 1 section velocity at 840s
Figure 13 shows the 3D view of the simulated casting for alloy A8011 rectangular 2. In Figure 14, a section velocity of the melt is presented showing a level of motion in the casting 5s after pouring. The centre region of the casting indicated some motion towards the sprue ingate. Figure 13 shows the 3D view of the simulated casting for alloy A8011 rectangular 2. A section temperature at 480s is presented in Figure 15. This shows the metal temperature at about 350 °C except for the Sprue area. In Figure 16, a section velocity of the melt is presented showing a level of motion in the casting 5s after pouring. The low liquid fraction shows that the metal is completely solidified except for the small part of the Sprue where there exists a relatively high liquid fraction.
4 Conclusion

The models developed were validated using experimental data. From the Finite Element Analysis, a helpful insight has been given to the nature of liquid metal velocity during mould filling, pressure contours that develop during solidification and temperature distribution as the metal cools. A comparison of the temperature profiles generated from the experiments and simulations show that in 64% of the processes, there were no significant differences between the experimental and simulated values. However, in comparing the Niyama values from the experiments and simulations, there were no significant differences in 46% of the processes. This work has been able to establish experimentally and analytically, threshold Niyama values of 0.143 (°C-s)\(^{1/2}\)/mm for A8011. Below this threshold value, it is expected that shrinkage will occur in castings from these metals. With this conclusion, the presence of shrinkage in these alloys can be controlled.

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## APPENDICES

### APPENDIX A. READINGS FOR ALLOY A8011 CYLINDRICAL SHAPE (Ø50mm × 200mm)

| Time | Exp. temp phase 2/P1 | Exp. temp phase 2/P2 | Sum temp P2(smp1) | Sum temp P2(smp2) | P2 - P1 | Exp. thermal gradient | Exp. cooling rate | Exp. Nyma (N) | SM P2-SMP 2 | SM Thermal Gradient | SM Coolin √ R | SM √ R | SM Nyma |
|------|---------------------|---------------------|-------------------|-------------------|----------|----------------------|------------------|--------------|--------------|-------------------|----------------|----------|----------|
| 20   | 782                 | 825                 | 654.29            | 645.09            | 33       | 1.32                 | 3.25             | 1.77         | 0.34         | 8.20              | 0.328          | 0.292    | 0.54       | 0.606       |
| 40   | 720                 | 752                 | 645.27            | 640.34            | 32       | 1.28                 | 2.2              | 1.48         | 0.86         | 5.05              | 0.201          | 0.366    | 0.58       | 0.343       |
| 60   | 701                 | 708                 | 633.56            | 633.36            | 3        | 0.28                 | 2.6              | 1.26         | 0.22         | 5.20              | 0.208          | 0.350    | 0.59       | 0.352       |
| 80   | 657                 | 676                 | 632.25            | 626.37            | 29       | 0.76                 | 2               | 1.00         | 0.76         | 5.38              | 0.215          | 0.362    | 0.60       | 0.358       |
| 100  | 643                 | 656                 | 624.43            | 619.13            | 13       | 0.52                 | 0.2              | 0.31         | 1.64         | 5.30              | 0.242          | 0.378    | 0.62       | 0.345       |
| 120  | 643                 | 654                 | 626.54            | 611.57            | 15       | 0.6                  | 0               | 0.00         | 0.00         | 4.98              | 0.199          | 0.402    | 0.63       | 0.334       |
| 140  | 643                 | 658                 | 606.22            | 603.52            | 15       | 0.5                  | 0.05             | 0.22         | 0.00         | 4.59              | 0.184          | 0.420    | 0.64       | 0.283       |
| 160  | 643                 | 655                 | 580.37            | 595.22            | 16       | 0.64                 | 0               | 0.00         | 0.00         | 4.24              | 0.170          | 0.433    | 0.65       | 0.242       |
| 180  | 623                 | 655                 | 590.49            | 586.47            | 35       | 1.44                 | 0               | 0.00         | 0.00         | 4.00              | 0.162          | 0.442    | 0.66       | 0.234       |
| 200  | 623                 | 659                 | 582.55            | 577.64            | 36       | 1.44                 | 0               | 0.00         | 0.00         | 3.32              | 0.156          | 0.446    | 0.66       | 0.232       |
| 220  | 623                 | 659                 | 572.59            | 558.71            | 36       | 1.44                 | 0.05             | 0.22         | 6.44         | 3.38              | 0.155          | 0.448    | 0.66       | 0.264       |
| 240  | 629                 | 653                 | 558.95            | 558.76            | 39       | 1.56                 | 0               | 0.00         | 0.00         | 3.94              | 0.157          | 0.445    | 0.66       | 0.247       |
| 260  | 628                 | 658                 | 550.95            | 550.85            | 40       | 1.5                  | 0.1              | 0.31         | 5.06         | 4.09              | 0.164          | 0.439    | 0.66       | 0.247       |
| 280  | 624                 | 656                 | 545.44            | 542.07            | 42       | 1.68                 | 0.05             | 0.22         | 7.51         | 4.38              | 0.175          | 0.428    | 0.63       | 0.267       |
| 300  | 612                 | 655                 | 538.31            | 533.53            | 43       | 1.72                 | 0.1              | 0.22         | 7.69         | 4.90              | 0.192          | 0.402    | 0.64       | 0.299       |
| 320  | 610                 | 654                 | 530.66            | 525.26            | 44       | 1.76                 | 0.15             | 0.31         | 5.56         | 5.40              | 0.206          | 0.397    | 0.63       | 0.343       |
| 340  | 607                 | 652                 | 523.24            | 517.32            | 45       | 1.8                  | 0.2              | 0.38         | 4.64         | 5.92              | 0.287          | 0.386    | 0.61       | 0.381       |
| 360  | 606                 | 649                 | 526.06            | 509.61            | 43       | 1.72                 | 0.65             | 0.44         | 3.84         | 6.47              | 0.259          | 0.372    | 0.60       | 0.425       |
| 380  | 605                 | 645                 | 509.32            | 502.17            | 40       | 1.6                  | 0.35             | 0.80         | 1.98         | 7.15              | 0.288          | 0.357    | 0.58       | 0.479       |
| 400  | 604                 | 632                 | 500.78            | 495.09            | 28       | 1.12                 | 1.1              | 0.97         | 1.14         | 7.75              | 0.320          | 0.347    | 0.58       | 0.527       |
| 420  | 602                 | 613                 | 436.31            | 488.09            | 12       | 0.48                 | 1.1              | 1.08         | 0.45         | 8.21              | 0.326          | 0.340    | 0.58       | 0.563       |
| 440  | 599                 | 592                 | 489.87            | 481.29            | 2        | 0.08                 | 0.85             | 0.92         | 0.08         | 8.58              | 0.343          | 0.334    | 0.57       | 0.599       |

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### APPENDIX B. READING FOR ALLOY A8011 RECTANGULAR SHAPE (200MM × 50MM × 39.3MM)

| Time | Exp temp probe 1 | Exp temp probe 2/P2 | SIM TEMP P1/SM P1 | Sm temp P2/SM P1 | P2-P1 | EXP Thermal gradient | Exp Cooling rate | Exp/Niyama | SM P2-SM P1 | SIM thermal gradient | SM cooling rate | SM/Niyama |
|------|-----------------|---------------------|------------------|-----------------|-------|---------------------|----------------|------------|-------------|---------------|---------------|-------------|------------|
| 20   | 640             | 685                 | 570.8            | 2               | 581.7 | 45.00               | 1.80           | 1.20       | 1.00        | 1.64         | 9.07          | 0.36        | 0.22       | 0.4         | 0.77         |
| 40   | 632             | 661                 | 559.9            | 9               | 557.2 | 29.00               | 1.16           | 0.05       | 0.22        | 5.19         | 3.28          | 0.13        | 0.33       | 0.5         | 0.23         |
| 60   | 632             | 662                 | 543.5            | 1               | 550.6 | 30.00               | 1.20           | 0.00       | 0.00        | 0.00         | 7.11          | 0.28        | 0.42       | 0.5         | 0.44         |
| 80   | 632             | 662                 | 534.0            | 5               | 542.3 | 30.00               | 1.16           | 0.05       | 0.22        | 5.37         | 8.24          | 0.33        | 0.48       | 0.6         | 0.48         |
| 100  | 632             | 661                 | 524.7            | 2               | 532.7 | 29.00               | 1.20           | 0.00       | 0.00        | 0.00         | 8.04          | 0.32        | 0.48       | 0.6         | 0.47         |
| 120  | 631             | 661                 | 515.3            | 9               | 523.2 | 30.00               | 1.24           | 0.00       | 0.00        | 0.00         | 7.84          | 0.31        | 0.51       | 0.7         | 0.44         |
| 140  | 630             | 661                 | 505.7            | 6               | 513.0 | 31.00               | 1.36           | 0.00       | 0.00        | 0.00         | 7.32          | 0.29        | 0.51       | 0.7         | 0.41         |
| 160  | 627             | 661                 | 496.0            | 9               | 502.8 | 34.00               | 1.52           | 0.05       | 0.00        | 0.00         | 6.75          | 0.27        | 0.52       | 0.7         | 0.38         |
| 180  | 623             | 661                 | 485.8            | 4               | 492.5 | 38.00               | 1.68           | 0.05       | 0.22        | 6.80         | 6.23          | 0.25        | 0.52       | 0.7         | 0.35         |
| 200  | 618             | 660                 | 476.4            | 0               | 482.7 | 42.00               | 1.68           | 0.05       | 0.22        | 7.51         | 5.71          | 0.23        | 0.52       | 0.7         | 0.32         |
| 220  | 612             | 659                 | 466.5            | 0               | 471.8 | 47.00               | 1.88           | 0.05       | 0.22        | 8.41         | 5.33          | 0.21        | 0.50       | 0.7         | 0.30         |
| 240  | 606             | 658                 | 456.7            | 6               | 461.8 | 52.00               | 2.08           | 0.10       | 0.32        | 6.58         | 5.09          | 0.20        | 0.50       | 0.7         | 0.29         |
| 260  | 599             | 656                 | 447.0            | 1               | 451.8 | 57.00               | 2.28           | 0.10       | 0.32        | 7.21         | 4.85          | 0.19        | 0.49       | 0.7         | 0.28         |
| 280  | 592             | 654                 | 437.5            | 9               | 442.1 | 62.00               | 2.48           | 0.25       | 0.50        | 4.96         | 4.51          | 0.18        | 0.48       | 0.6         | 0.26         |
| 300  | 585             | 649                 | 428.3            | 0               | 432.4 | 64.00               | 2.56           | 0.40       | 0.63        | 4.05         | 4.12          | 0.16        | 0.48       | 0.6         | 0.24         |
| 320  | 577             | 641                 | 419.1            | 3               | 422.9 | 64.00               | 2.56           | 1.10       | 1.05        | 2.44         | 3.82          | 0.15        | 0.45       | 0.6         | 0.23         |
| 340  | 569             | 619                 | 410.1            | 1               | 413.8 | 50.00               | 2.00           | 1.05       | 1.02        | 1.95         | 3.74          | 0.15        | 0.45       | 0.6         | 0.22         |
| 360  | 559             | 598                 | 401.0            | 9               | 404.7 | 39.00               | 1.56           | 0.95       | 0.97        | 1.80         | 3.56          | 0.15        | 0.45       | 0.5         | 0.22         |
| 380  | 547             | 579                 | 392.5            | 9               | 396.0 | 32.00               | 1.08           | 0.85       | 0.92        | 1.39         | 3.49          | 0.14        | 0.43       | 0.5         | 0.22         |
| 400  | 536             | 562                 | 384.1            | 8               | 387.4 | 27.00               | 1.08           | 0.75       | 0.87        | 1.25         | 3.30          | 0.13        | 0.42       | 0.6         | 0.20         |
| 420  | 529             | 547                 | 375.9            | 6               | 379.0 | 24.00               | 0.96           | 0.70       | 0.84        | 1.15         | 3.13          | 0.13        | 0.41       | 0.6         | 0.20         |
| 440  | 512             | 533                 | 367.5            | 8               | 370.9 | 21.00               | 0.84           | 0.60       | 0.77        | 1.08         | 2.96          | 0.12        | 0.40       | 0.6         | 0.19         |
| 460  | 500             | 521                 | 360.0            | 6               | 362.8 | 21.00               | 0.84           | 0.65       | 0.81        | 1.04         | 2.85          | 0.11        | 0.38       | 0.6         | 0.18         |
| 480  | 490             | 508                 | 352.4            | 7               | 355.2 | 18.00               | 0.72           | 25.40      | 5.04        | 0.14         | 2.78          | 0.11        | 17.76      | 4.2         | 0.03         |