Series Solution of One-Dimensional Stationary Thermal Explosion Problems

Ahmed R. Shouman, A. Burl Donaldson, John Werth

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SERIES SOLUTION OF ONE-DIMENSIONAL STATIONARY
THERMAL EXPLOSION PROBLEMS

Ahmed R. Shouman
Professor of Mechanical Engineering
New Mexico State University
Las Cruces, New Mexico

A. Burl Donaldson
Detonating Components Div. 2513
Sandia Laboratories
Albuquerque, New Mexico 87115

and

John Werth
Assistant Professor of Mathematics
University of Nevada
Las Vegas, Nevada

ABSTRACT

A series solution is obtained for one-dimensional, stationary thermal explosion problems by expressing the temperature in the reactive material in terms of an even power series of the position variable. Coefficients of this series are determined by replacing terms in the energy equation with their series equivalents and by equating coefficients of like powers. The resulting series is examined for the condition of incipient thermal explosion, and the resulting critical parameters are tabulated. Specific geometries treated are the slab and the solid cylinder and sphere.

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Nomenclature

Variables

a, b, c	subscripted coefficients used to represent temperature profile
E	activation energy
K	thermal conductivity of reactant
k	integer which specifies geometry
L	half-thickness of reactant
n	index used in series
p	index used in series
Q	heat of reaction
R	gas constant
T	absolute temperature
x	dimensional position
Z	pre-exponential (frequency factor)
δ	critical parameter
θ	nondimensional temperature ($\equiv RT/E$)
ξ	nondimensional position $\left[\equiv \left(\frac{\rho Q Z R}{K E} \right)^{1/2} x \right]$
ρ	density of reactant

Subscripts

m	maximum
s	surface

Superscript

*	critical
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SERIES SOLUTION OF ONE-DIMENSIONAL STATIONARY THERMAL EXPLOSION PROBLEMS

Introduction

In general, the reaction rate of exothermically (self-heating) decomposing materials increases as absolute temperature increases. As a result, an increase in the boundary temperature of a self-heating body results in a correlative increase in the internal heating rate. At some sufficiently high boundary temperature, the internal heat generation for a given body can marginally be conducted to and dissipated at the boundary. When the boundary temperature is raised above this point, accelerating self-heating and finally thermal explosion will occur within the body.

The boundary temperature at which thermal explosion occurs is a function of the characteristics of the reactive material and its dimension(s). Similarly, if a boundary temperature is specified for a given material and the dimension of the body is increased, a condition occurs in which any further increase in dimension leads to thermal explosion. This dimension for impending thermal explosion is a function of the characteristics of the reactive material and its boundary temperature(s). Hence, either critical thickness for a given boundary temperature or critical boundary temperature for a given thickness can specify the condition of incipient thermal explosion.

Investigation of the theory of thermal explosion began with the work of Semenov [1]. Semenov considered a reactive body to be of uniform temperature, and he determined the maximum value of this temperature as a function of dissipation at the boundary. Frank-Kamenetskii [2] considered the problem

of a symmetric slab with a specified boundary temperature and internal temperature gradients. In his approach, an approximate form of the self-heating term (based on the characteristics of common explosives) was used to allow solution. By this method, a combination of thickness and boundary temperature was found to be invariant at the critical condition. Chambré [3] extended the Frank-Kamenetskii exponential approximation to the analysis of cylinders and spheres and found a similar invariance in Frank-Kamenetskii's critical condition for these geometries. More recent investigations [4, 5, 6] have shown that the invariance is valid for large thickness (or small boundary temperature) but does not hold for all possible conditions.

The series solution method used in this study is similar to a method which has been widely applied to solving ordinary linear differential equations with variable coefficients, i.e., the method of Frobenius. The present approach differs from the series method of Reference 5 wherein the coefficients were evaluated from the boundary conditions and the energy-equation at internal location(s).

Analysis

If the standard Arrhenius model is assumed for heat production, the dimensionless stationary energy equation and standard boundary conditions (B.C.) are

$$\frac{d^2\theta}{d\xi^2} + \frac{k}{\xi} \frac{d\theta}{d\xi} = -\exp(-1/\theta) \quad (1)$$

$$\text{B.C. 1.} \quad \frac{d\theta}{d\xi}(0) = 0 [\theta(0) = \theta_m]$$

$$2. \quad \theta(L) = \theta_s$$

where

$k = 0$ for slab geometry

$k = 1$ for cylinder geometry

$k = 2$ for sphere geometry

By the steady-state nature of Eq. (1), no depletion is presumed. This is of course an approximation because any self-heating is necessarily a result of reaction. However, at temperatures only moderately below the critical temperature, self-heating is negligible; and, at the critical temperature or above, thermal explosion results after only a small fraction of the material has been consumed. Hence, Eq. (1) is a good representation of a quasi-stationary process. Boundary Condition 1 is a result of symmetry about the mid-plane of a slab, the center of an infinite cylinder, or the center of a sphere. The temperature at this location is designated θ_m ; although it is normally an unknown quantity, it will be used throughout the analysis and will subsequently be related to the boundary temperature θ_s at the outside surface ($\xi = L$).

Because thermal explosion has been shown to be a result of an upward displacement of internal temperature for this type of problem [6] and because the reaction rate is highest at the highest temperature, θ_m , a series of the form

$$\theta = \theta_m - \sum_{n=1}^{\infty} a(1, n) \xi^{2n} \quad (2)$$

is suggested. Only even powers of ξ are used for the purpose of satisfying the condition of symmetry about the origin. The series can be truncated at any integer n ; however, the accuracy of the final solution is improved as the number of terms increases.

Equation (2) is now substituted into the left side of Eq. (1) to give

$$\frac{d^2\theta}{d\xi^2} + \frac{k}{\xi} \frac{d\theta}{d\xi} = -\sum_{n=1}^{\infty} \left\{ 2n[(2n-1) + k] a(1, n) \xi^{2n-2} \right\} . \quad (3)$$

Inversion of Eq. (2) for the exponential term of the right side of Eq. (1) can be accomplished by the binomial expansion. The result is

$$\frac{1}{\theta} = \frac{1}{\theta_m} \sum_{p=0}^{\infty} \theta_m^{-p} \left(\sum_{n=1}^{\infty} a(1, n) \xi^{2n} \right)^p . \quad (4)$$

Because $\theta_s < \theta_m$, the expansion is valid for all $\xi \leq L$.

Substitution of Eqs. (3) and (4) into Eq. (1) yields

$$\begin{aligned} & \sum_{n=1}^{\infty} \left\{ 2n[(2n-1) + k] a(1, n) \xi^{2n-2} \right\} \\ &= \exp\left(-\frac{1}{\theta_m}\right) \cdot \prod_{p=1}^{\infty} \exp\left[\theta_m^{-(p+1)} \left(\sum_{n=1}^{\infty} a(1, n) \xi^{2n} \right)^p \right] . \end{aligned} \quad (5)$$

Now, to complete the solution, the exponential can be expressed as a series. Then by equating coefficients of like powers of ξ in Eq. (5), the $a(1, n)$'s can be determined and Eq. (2) then expresses the temperature profile. However, by hand this procedure is rather tedious for the higher terms in the series. Because the series becomes more slowly convergent as the geometry changes from slab to cylinder to sphere, machine computation of the coefficients is required in order to obtain a sufficient number of terms. Thus, the following discussion will briefly outline an algorithm which was used for computer determination of the $a(1, n)$'s.

For shorthand, define

$$y = \sum_{n=1}^{\infty} a(1, n) \xi^{2n} .$$

Then the product term in Eq. (5) can be written

$$\prod_{p=1}^{\infty} \exp \left(- \frac{y^p}{\theta_m^{p+1}} \right)$$

By writing the exponential as a series and using series multiplication, the alternate form

$$\prod_{p=1}^{\infty} \exp \left(- \frac{y^p}{\theta_m^{p+1}} \right) = \sum_{j=0}^{\infty} b(r, j) y^j$$

can be expressed. Here, the $b(r, j)$'s represent the collection of coefficients from all of the y^j terms. It can be shown that the $b(r, j)$'s can be related to lower coefficients by

$$b(r, j) = \sum_{\ell=0}^{\ell \leq \frac{j}{r}} \frac{(-1)^\ell b(r-1, j-r\ell)}{\ell! \theta_m^{(r+1)\ell}} \quad . \quad (7)$$

Using the definition of y , the y^j 's can be expressed as

$$y^j = \sum_{i=j}^{\infty} a(j, i) \xi^{2i} \quad . \quad (8)$$

It can then be shown that the $a(j, i)$'s are related to lower order coefficients by the expression

$$a(j, i) = \sum_{q=1}^{q=i+1+j} a(1, q) a(j-1, i-q) \quad . \quad (9)$$

Now, substitution of Eq. (8) into Eq. (6) yields

$$\prod_{p=1}^{\infty} \exp \left(- \frac{y^p}{\theta_m^{p+1}} \right) = b(r, 0) + \sum_{n=1}^{\infty} c(n) \xi^{2n} \quad , \quad (10)$$

where

$$c(n) = \sum_{m=1}^n b(n, m) a(n, m) \quad .$$

Recognizing that $b(r, 0) = 1$, Eqs. (10) and (5) can be combined to give

$$\sum_{n=1}^{\infty} 2n[(2n-1)+k] a(1, n) \xi^{2n-2} = 1 + \sum_{n=1}^{\infty} c(n) \xi^{2n} . \quad (11)$$

Finally, by equating like powers of ξ in Eq. (11),

$$a(1, n) = \frac{\exp(-1/\theta_m)}{2n[(2n-1)+k]} c(n-1) . \quad (12)$$

The symbolic computer language Formac was used with the above equations to determine the $a(1, n)$'s as functions of θ_m for $k = 0, 1, 2$ and $n = 1, 2, 3, \dots$. These are given in Tables 1 through 3 for the slab, cylinder, and sphere geometries, respectively.

For a self-heating material with a fixed boundary temperature, the criterion for thermal explosion has been shown to be [6]

$$\left(\frac{\partial L}{\partial \theta_m} \right)_{\theta_s} = 0 . \quad (13)$$

That is, for a constant θ_s , at the onset of explosion an infinitesimal increase in length is accompanied by a large increase in θ_m . Mathematically, on a graph of L as a function of θ_m for constant θ_s , there is a region in which, for each L , three values of θ_m are found; thermal explosion corresponds to the relative maxima ($L = L_1^*$), and, although no physical interpretation has yet been shown, the relative minima is called the extinction limit ($L = L_2^*$). To examine this criterion, Eq. (2) is evaluated at $\xi = L$, ($\theta = \theta_s$), and the operation of Eq. (13)

is taken. Thus,

$$0 = 1 - \sum_{n=1}^{\infty} \left[\frac{\partial a(1, n)}{\partial \theta_m} \right]_{\theta_s} L^{*2n}, \quad (14)$$

where the L^* 's refer to the critical length for the onset of thermal explosion or extinction. By defining a critical delta based on θ_m ,

$$\delta_m = \frac{L^{*2}}{\theta_m^2 \exp(1/\theta_m)}, \quad (15)$$

Equation (14) can be written as

$$0 = 1 - \sum_{n=1}^{\infty} \theta_m^2 \exp(1/\theta_m) \left[\frac{\partial a(1, n)}{\partial \theta} \right]_{\theta_s} \delta_m^n. \quad (16)$$

Equation (16) can be solved to give δ_m as a function of θ_m . Then the boundary temperature corresponding to this critical condition is given by evaluating Eq. (2) at $L = L_1^*$. From θ_s at L_1^* the Frank-Kamenetskii critical delta

$$\delta_s = \frac{L^{*2}}{\theta_s^2 \exp(1/\theta_s)} \quad (17)$$

can be determined.

Tables 4 through 6 give θ_m , θ_s , and δ_s at the critical condition for thermal explosion as function of θ_m for the slab, cylinder, and sphere, respectively.

The speed of convergence of the series solution varies with the geometry. As a consequence, 15 terms give very good agreement with the values given in Reference 4 for $k = 0$, for $k = 1$ there is some deterioration, and for $k = 2$ convergence is good for only a narrow range of θ .

Equation (2) can be used to calculate the temperature profile in a material. Tables 4 through 6 show that the profile is very flat at the critical condition for small values of θ_m and, conversely, the profile is steep for large values of θ_m . This illustrates the reason why the Frank-Kamenetskii exponential approximation gives good results for small values of θ_s (or θ_m) but does not give good results for large values of θ_s . That is, the exponential approximation is valid for only small departures from θ_s .

Conclusions

The series solution method shown herein is a rather general and straightforward method which gives values in good agreement with other methods utilizing substantially more computer time and programming sophistication. The method appears to be well suited to investigating other problems involving nonlinear heat sources/sinks as well as variations of the thermal explosion problem, such as composites and heat flux or mixed boundary conditions.

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Table 1

The $a(1, n)$'s for Cartesian Geometry ($k = 0$)

$$a(1, 1) = \left[5.00000 \times 10^{-1} \right] \exp (-1/\theta_m)$$

$$a(1, 2) = \left[-4.16667 \times 10^{-2} \theta_m^{-2} \right] \exp (-2/\theta_m)$$

$$a(1, 3) = \left[-8.33333 \times 10^{-3} \theta_m^{-3} + 5.55555 \times 10^{-3} \theta_m^{-4} \right] \exp (-3/\theta_m)$$

$$a(1, 4) = \left[-2.23214 \times 10^{-3} \theta_m^{-4} + 3.12500 \times 10^{-3} \theta_m^{-5} \right. \\ \left. - 8.43254 \times 10^{-4} \theta_m^{-6} \right] \exp (-4/\theta_m)$$

$$a(1, 5) = \left[-6.94444 \times 10^{-4} \theta_m^{-5} + 1.50628 \times 10^{-3} \theta_m^{-6} \right. \\ \left. - 8.56481 \times 10^{-4} \theta_m^{-7} + 1.36684 \times 10^{-4} \theta_m^{-8} \right] \exp (-5/\theta_m)$$

$$a(1, 6) = \left[-2.36742 \times 10^{-4} \theta_m^{-6} + 7.00833 \times 10^{-4} \theta_m^{-7} \right. \\ \left. - 6.20929 \times 10^{-4} \theta_m^{-8} + 2.08408 \times 10^{-4} \theta_m^{-9} \right. \\ \left. - 2.30813 \times 10^{-5} \theta_m^{-10} \right] \exp (6/\theta_m)$$

$$a(1, 7) = \left[-8.58516 \times 10^{-5} \theta_m^{-7} + 3.23381 \times 10^{-4} \theta_m^{-8} \right. \\ \left. - 3.93322 \times 10^{-4} \theta_m^{-9} + 2.05838 \times 10^{-4} \theta_m^{-10} \right. \\ \left. - 4.78033 \times 10^{-5} \theta_m^{-11} + 4.00907 \times 10^{-6} \theta_m^{-12} \right] \exp (-7/\theta_m)$$

Table 1 (cont.)

$$a(1, 8) = \left[-3.25521 \times 10^{-5} \theta_m^{-8} + 1.49224 \times 10^{-4} \theta_m^{-9} \right. \\
-2.32195 \times 10^{-4} \theta_m^{-10} + 1.67094 \times 10^{-4} \theta_m^{-11} \\
-6.04517 \times 10^{-5} \theta_m^{-12} + 1.05995 \times 10^{-5} \theta_m^{-13} \\
\left. -7.10857 \times 10^{-7} \right] \exp(-8/\theta_m)$$

$$a(1, 9) = \left[-1.27655 \times 10^{-5} \theta_m^{-9} + 6.90601 \times 10^{-5} \theta_m^{-10} \right. \\
-1.31417 \times 10^{-4} \theta_m^{-11} + 1.21234 \times 10^{-4} \theta_m^{-12} \\
-6.03207 \times 10^{-5} \theta_m^{-13} + 1.64531 \times 10^{-4} \theta_m^{-14} \\
\left. -2.30057 \times 10^{-6} \theta_m^{-15} + 1.28044 \times 10^{-7} \theta_m^{-16} \right] \exp(-9/\theta_m)$$

$$a(1, 10) = \left[-5.13980 \times 10^{-6} \theta_m^{-10} + 3.20835 \times 10^{-5} \theta_m^{-11} \right. \\
-7.23646 \times 10^{-5} \theta_m^{-12} + 8.18138 \times 10^{-5} \theta_m^{-13} \\
-5.22184 \times 10^{-5} \theta_m^{-14} + 1.95788 \times 10^{-5} \theta_m^{-15} \\
-4.25218 \times 10^{-6} \theta_m^{-16} + 4.92197 \times 10^{-7} \theta_m^{-17} \\
\left. -2.33525 \times 10^{-8} \theta_m^{-18} \right] \exp(-10/\theta_m)$$

Table 1 (cont.)

$$a(1, 11) = \left[-2.11377 \times 10^{-6} \theta_m^{-11} + 1.49649 \times 10^{-5} \theta_m^{-12} \right. \\
- 3.90974 \times 10^{-5} \theta_m^{-13} + 5.25004 \times 10^{-5} \theta_m^{-14} \\
- 4.11049 \times 10^{-5} \theta_m^{-15} + 1.97709 \times 10^{-5} \theta_m^{-16} \\
- 5.89786 \times 10^{-6} \theta_m^{-17} + 1.05876 \times 10^{-6} \theta_m^{-18} \\
\left. - 1.04236 \times 10^{-7} \theta_m^{-19} + 4.30110 \times 10^{-9} \theta_m^{-20} \right] \exp(-11/\theta_m)$$

$$a(1, 12) = \left[-8.84567 \times 10^{-7} \theta_m^{-12} + 7.00718 \times 10^{-6} \theta_m^{-13} \right. \\
- 2.08353 \times 10^{-5} \theta_m^{-14} + 3.02273 \times 10^{-5} \theta_m^{-15} \\
- 3.02274 \times 10^{-5} \theta_m^{-16} + 1.78409 \times 10^{-5} \theta_m^{-17} \\
- 6.82540 \times 10^{-6} \theta_m^{-18} + 1.68143 \times 10^{-6} \theta_m^{-19} \\
- 2.56352 \times 10^{-7} \theta_m^{-20} + 2.19101 \times 10^{-8} \theta_m^{-21} \\
\left. - 7.99120 \times 10^{-10} \theta_m^{-22} \right] \exp(-12/\theta_m)$$

$$a(1, 13) = \left[-3.75601 \times 10^{-7} \theta_m^{-13} + 3.29292 \times 10^{-6} \theta_m^{-14} \right. \\
- 1.09896 \times 10^{-5} \theta_m^{-15} + 1.95281 \times 10^{-5} \theta_m^{-16} \\
- 2.11213 \times 10^{-5} \theta_m^{-17} + 1.48230 \times 10^{-5} \theta_m^{-18} \\
- 6.96209 \times 10^{-6} \theta_m^{-19} + 2.19850 \times 10^{-6} \theta_m^{-20} \\
- 4.59542 \times 10^{-7} \theta_m^{-21} + 6.07385 \times 10^{-8} \theta_m^{-22} \\
\left. - 4.57933 \times 10^{-9} \theta_m^{-23} + 1.49479 \times 10^{-10} \theta_m^{-24} \right] \exp(-13/\theta_m)$$

Table 1 (cont.)

$$\begin{aligned}
a(1, 14) = & \left[-1.61469 \times 10^{-7} \theta_m^{-14} + 1.55262 \times 10^{-6} \theta_m^{-15} \right. \\
& -5.75077 \times 10^{-6} \theta_m^{-16} + 1.14891 \times 10^{-5} \theta_m^{-17} \\
& -1.41841 \times 10^{-5} \theta_m^{-18} + 1.15785 \times 10^{-5} \theta_m^{-19} \\
& -6.46762 \times 10^{-6} \theta_m^{-20} + 2.50576 \times 10^{-6} \theta_m^{-21} \\
& -6.71001 \times 10^{-7} \theta_m^{-22} + 1.21476 \times 10^{-7} \theta_m^{-23} \\
& -1.41448 \times 10^{-8} \theta_m^{-24} + 9.52882 \times 10^{-10} \theta_m^{-25} \\
& \left. -2.81271 \times 10^{-11} \theta_m^{-26} \right] \exp(-14/\theta_m)
\end{aligned}$$

$$\begin{aligned}
a(1, 15) = & \left[-7.01554 \times 10^{-8} \theta_m^{-15} + 7.34307 \times 10^{-7} \theta_m^{-16} \right. \\
& -2.99061 \times 10^{-6} \theta_m^{-17} + 6.64149 \times 10^{-6} \theta_m^{-18} \\
& -9.22841 \times 10^{-6} \theta_m^{-19} + 8.60448 \times 10^{-6} \theta_m^{-20} \\
& -5.58978 \times 10^{-6} \theta_m^{-21} + 2.57683 \times 10^{-6} \theta_m^{-22} \\
& -8.46332 \times 10^{-7} \theta_m^{-23} + 1.96166 \times 10^{-7} \theta_m^{-24} \\
& -3.12578 \times 10^{-8} \theta_m^{-25} + 3.24820 \times 10^{-9} \theta_m^{-26} \\
& \left. -1.97584 \times 10^{-10} \theta_m^{-27} + 5.31977 \times 10^{-12} \theta_m^{-28} \right] \exp(-15/\theta_m)
\end{aligned}$$

Table 2

The $a(1, n)$'s for Cylindrical Geometry ($k = 1$)

$$a(1, 1) = \left[2.50000 \times 10^{-1} \right] \exp(-1/\theta_m)$$

$$a(1, 2) = \left[1.56250 \times 10^{-2} \theta_m^{-2} \right] \exp(-2/\theta_m)$$

$$a(1, 3) = \left[-1.73611 \times 10^{-3} \theta_m^{-3} + 1.30208 \times 10^{-3} \theta_m^{-4} \right] \exp(-3/\theta_m)$$

$$a(1, 4) = \left[-2.44141 \times 10^{-4} \theta_m^{-4} + 3.03338 \times 10^{-4} \theta_m^{-5} \right. \\ \left. - 1.22070 \times 10^{-4} \theta_m^{-6} \right] \exp(-4/\theta_m)$$

$$a(1, 5) = \left[-3.90625 \times 10^{-5} \theta_m^{-5} + 9.90126 \times 10^{-5} \theta_m^{-6} \right. \\ \left. - 6.60536 \times 10^{-5} \theta_m^{-7} + 1.22070 \times 10^{-5} \theta_m^{-8} \right] \exp(-5/\theta_m)$$

$$a(1, 6) = \left[-6.78168 \times 10^{-6} \theta_m^{-6} + 2.37246 \times 10^{-5} \theta_m^{-7} \right. \\ \left. - 2.50357 \times 10^{-5} \theta_m^{-8} + 9.90126 \times 10^{-6} \theta_m^{-9} \right. \\ \left. - 1.27157 \times 10^{-6} \theta_m^{-10} \right] \exp(-6/\theta_m)$$

$$a(1, 7) = \left[-1.24562 \times 10^{-6} \theta_m^{-7} + 5.59247 \times 10^{-6} \theta_m^{-8} \right. \\ \left. - 8.19798 \times 10^{-6} \theta_m^{-9} + 5.12651 \times 10^{-6} \theta_m^{-10} \right. \\ \left. - 1.40179 \times 10^{-6} \theta_m^{-11} + 1.36239 \times 10^{-7} \theta_m^{-12} \right] \exp(-7/\theta_m)$$

Table 2 (cont.)

$$a(1, 8) = \left[-2.38419 \times 10^{-7} \theta_m^{-8} + 1.31166 \times 10^{-6} \theta_m^{-9} \right. \\
- 2.48348 \times 10^{-6} \theta_m^{-10} + 2.16036 \times 10^{-6} \theta_m^{-11} \\
- 9.32120 \times 10^{-7} \theta_m^{-12} + 1.91980 \times 10^{-7} \theta_m^{-13} \\
\left. - 1.49012 \times 10^{-8} \theta_m^{-14} \right] \exp(-8/\theta_m)$$

$$a(1, 9) = \left[-4.70950 \times 10^{-8} \theta_m^{-9} + 3.07481 \times 10^{-7} \theta_m^{-10} \right. \\
- 7.17642 \times 10^{-7} \theta_m^{-11} + 8.08084 \times 10^{-7} \theta_m^{-12} \\
- 4.84784 \times 10^{-7} \theta_m^{-13} + 1.57152 \times 10^{-7} \theta_m^{-14} \\
\left. - 2.57416 \times 10^{-8} \theta_m^{-15} + 1.65568 \times 10^{-9} \theta_m^{-16} \right] \exp(-9/\theta_m)$$

$$a(1, 10) = \left[-9.53674 \times 10^{-9} \theta_m^{-10} + 7.21808 \times 10^{-8} \theta_m^{-11} \right. \\
- 2.01017 \times 10^{-7} \theta_m^{-12} + 2.79715 \times 10^{-7} \theta_m^{-13} \\
- 2.17306 \times 10^{-7} \theta_m^{-14} + 9.78279 \times 10^{-8} \theta_m^{-15} \\
- 2.51571 \times 10^{-8} \theta_m^{-16} + 3.40222 \times 10^{-9} \theta_m^{-17} \\
\left. - 1.86245 \times 10^{-10} \theta_m^{-18} \right] \exp(-10/\theta_m)$$

Table 2 (cont.)

$$\begin{aligned}
 a(1, 11) = & \left[-1.97040 \times 10^{-9} \theta_m^{-11} + 1.69819 \times 10^{-8} \theta_m^{-12} \right. \\
 & -5.50949 \times 10^{-8} \theta_m^{-13} + 9.17128 \times 10^{-8} \theta_m^{-14} \\
 & -8.81281 \times 10^{-8} \theta_m^{-15} + 5.13564 \times 10^{-8} \theta_m^{-16} \\
 & -1.83131 \times 10^{-8} \theta_m^{-17} + 3.87880 \times 10^{-9} \theta_m^{-18} \\
 & \left. -4.45073 \times 10^{-10} \theta_m^{-19} + 2.11664 \times 10^{-11} \theta_m^{-20} \right] \exp(-11/\theta_m)
 \end{aligned}$$

$$\begin{aligned}
 a(1, 12) = & \left[-4.139211 \times 10^{-10} \theta_m^{-12} + 4.00531 \times 10^{-9} \theta_m^{-13} \right. \\
 & -1.48628 \times 10^{-8} \theta_m^{-14} + 2.88957 \times 10^{-8} \theta_m^{-15} \\
 & -3.32555 \times 10^{-8} \theta_m^{-16} + 2.39726 \times 10^{-8} \theta_m^{-17} \\
 & -1.10567 \times 10^{-8} \theta_m^{-18} + 3.24227 \times 10^{-9} \theta_m^{-19} \\
 & -5.81359 \times 10^{-10} \theta_m^{-20} + 5.77830 \times 10^{-11} \theta_m^{-21} \\
 & \left. -2.42532 \times 10^{-12} \theta_m^{-22} \right] \exp(-12/\theta_m)
 \end{aligned}$$

$$\begin{aligned}
 a(1, 13) = & \left[-8.81725 \times 10^{-11} \theta_m^{-13} + 9.47104 \times 10^{-10} \theta_m^{-14} \right. \\
 & -3.96186 \times 10^{-9} \theta_m^{-15} + 8.83132 \times 10^{-9} \theta_m^{-16} \\
 & -1.18861 \times 10^{-8} \theta_m^{-17} + 1.02664 \times 10^{-8} \theta_m^{-18} \\
 & -5.85533 \times 10^{-9} \theta_m^{-19} + 2.21866 \times 10^{-9} \theta_m^{-20} \\
 & -5.49925 \times 10^{-10} \theta_m^{-21} + 8.52375 \times 10^{-11} \theta_m^{-22} \\
 & \left. -7.45853 \times 10^{-12} \theta_m^{-23} + 2.79845 \times 10^{-13} \theta_m^{-24} \right] \exp(-13/\theta_m)
 \end{aligned}$$

Table 2 (cont.)

$$\begin{aligned}
a(1, 14) = & \left[-1.90066 \times 10^{-11} \theta_m^{-14} + 2.24513 \times 10^{-10} \theta_m^{-15} \right. \\
& -1.04635 \times 10^{-9} \theta_m^{-16} + 2.63535 \times 10^{-9} \theta_m^{-17} \\
& -4.07229 \times 10^{-9} \theta_m^{-18} + 4.11593 \times 10^{-9} \theta_m^{-19} \\
& -2.81270 \times 10^{-9} \theta_m^{-20} + 1.31717 \times 10^{-9} \theta_m^{-21} \\
& -4.21417 \times 10^{-10} \theta_m^{-21} + 9.01592 \times 10^{-11} \theta_m^{-23} \\
& -1.22798 \times 10^{-11} \theta_m^{-23} + 9.58389 \times 10^{-13} \theta_m^{-25} \\
& \left. -3.24820 \times 10^{-14} \theta_m^{-25} \right] \exp(-14/\theta_m)
\end{aligned}$$

$$\begin{aligned}
a(1, 15) = & \left[-4.13921 \times 10^{-12} \theta_m^{-15} + 5.33477 \times 10^{-11} \theta_m^{-16} \right. \\
& -2.74326 \times 10^{-10} \theta_m^{-17} + 7.71444 \times 10^{-10} \theta_m^{-18} \\
& -1.34878 \times 10^{-9} \theta_m^{-19} + 1.56631 \times 10^{-9} \theta_m^{-20} \\
& -1.25277 \times 10^{-9} \theta_m^{-21} + 7.02736 \times 10^{-10} \theta_m^{-22} \\
& -2.77677 \times 10^{-10} \theta_m^{-23} + 7.66008 \times 10^{-11} \theta_m^{-24} \\
& -1.43806 \times 10^{-11} \theta_m^{-25} + 1.74398 \times 10^{-12} \theta_m^{-26} \\
& \left. -1.22706 \times 10^{-13} \theta_m^{-27} + 3.78956 \times 10^{-15} \theta_m^{-28} \right] \exp(-15/\theta_m)
\end{aligned}$$

Table 3

The $a(1, n)$'s for Spherical Geometry ($k = 2$)

$$a(1, 1) = \left[1.66667 \times 10^{-1} \right] \exp(-1/\theta_m)$$

$$a(1, 2) = \left[8.33333 \times 10^{-3} \theta_m^{-2} \right] \exp(-2/\theta_m)$$

$$a(1, 3) = \left[-6.61376 \times 10^{-4} \theta_m^{-3} + 5.29101 \times 10^{-4} \theta_m^{-4} \right] \exp(-3/\theta_m)$$

$$a(1, 4) = \left[-6.43004 \times 10^{-5} \theta_m^{-4} + 1.12066 \times 10^{-4} \theta_m^{-5} \right. \\ \left. - 3.73554 \times 10^{-5} \theta_m^{-6} \right] \exp(-4/\theta_m)$$

$$a(1, 5) = \left[-7.01459 \times 10^{-6} \theta_m^{-5} + 1.94237 \times 10^{-5} \theta_m^{-6} \right. \\ \left. - 1.40759 \times 10^{-5} \theta_m^{-7} + 2.80138 \times 10^{-6} \theta_m^{-8} \right] \exp(-5/\theta_m)$$

$$a(1, 6) = \left[-8.24364 \times 10^{-7} \theta_m^{-6} + 3.17362 \times 10^{-6} \theta_m^{-7} \right. \\ \left. - 3.67006 \times 10^{-6} \theta_m^{-8} + 1.57775 \times 10^{-6} \theta_m^{-9} \right. \\ \left. - 2.18422 \times 10^{-7} \theta_m^{-10} \right] \exp(-6/\theta_m)$$

$$a(1, 7) = \left[-1.02064 \times 10^{-7} \theta_m^{-7} + 5.07155 \times 10^{-7} \theta_m^{-8} \right. \\ \left. - 8.20484 \times 10^{-7} \theta_m^{-9} + 5.62042 \times 10^{-7} \theta_m^{-10} \right. \\ \left. - 1.66989 \times 10^{-7} \theta_m^{-11} + 1.74996 \times 10^{-8} \theta_m^{-12} \right] \exp(-7/\theta_m)$$

Table 3 (cont.)

$$a(1, 8) = \left[-1.31333 \times 10^{-8} \theta_m^{-8} + 8.03328 \times 10^{-8} \theta_m^{-9} \right. \\
-1.68845 \times 10^{-7} \theta_m^{-10} + 1.61942 \times 10^{-7} \theta_m^{-11} \\
-7.64389 \times 10^{-8} \theta_m^{-12} + 1.70931 \times 10^{-8} \theta_m^{-13} \\
\left. -1.43045 \times 10^{-9} \theta_m^{-14} \right] \exp(-8/\theta_m)$$

$$a(1, 9) = \left[-1.7486 \times 10^{-9} \theta_m^{-9} + 1.26849 \times 10^{-8} \theta_m^{-10} \right. \\
-3.30265 \times 10^{-8} \theta_m^{-11} + 4.12317 \times 10^{-8} \theta_m^{-12} \\
-2.72206 \times 10^{-8} \theta_m^{-13} + 9.63883 \times 10^{-9} \theta_m^{-14} \\
\left. -1.71270 \times 10^{-9} \theta_m^{-15} + 1.18743 \times 10^{-10} \theta_m^{-16} \right] \exp(-9/\theta_m)$$

$$a(1, 10) = \left[-2.36260 \times 10^{-10} \theta_m^{-10} + 2.00205 \times 10^{-9} \theta_m^{-11} \right. \\
-6.24581 \times 10^{-9} \theta_m^{-12} + 9.68248 \times 10^{-9} \theta_m^{-13} \\
-8.82090 \times 10^{-9} \theta_m^{-14} + 4.11386 \times 10^{-9} \theta_m^{-15} \\
-1.15388 \times 10^{-9} \theta_m^{-16} + 1.69133 \times 10^{-10} \theta_m^{-17} \\
\left. -9.97801 \times 10^{-12} \theta_m^{-18} \right] \exp(-10/\theta_m)$$

Table 3 (cont.)

$$\begin{aligned}
 a(1, 11) = & \left[-3.26841 \times 10^{-11} \theta_m^{-11} + 3.16240 \times 10^{-10} \theta_m^{-12} \right. \\
 & -1.15350 \times 10^{-9} \theta_m^{-13} + 2.14827 \times 10^{-9} \theta_m^{-14} \\
 & -2.29402 \times 10^{-9} \theta_m^{-15} + 1.47520 \times 10^{-9} \theta_m^{-16} \\
 & -5.76590 \times 10^{-10} \theta_m^{-17} + 1.33022 \times 10^{-10} \theta_m^{-18} \\
 & \left. -1.65298 \times 10^{-11} \theta_m^{-19} + 8.46795 \times 10^{-13} \theta_m^{-20} \right] \exp(-11/\theta_m)
 \end{aligned}$$

$$\begin{aligned}
 a(1, 12) = & \left[-4.59394 \times 10^{-12} \theta_m^{-12} + 5.00239 \times 10^{-11} \theta_m^{-13} \right. \\
 & -2.09363 \times 10^{-10} \theta_m^{-14} + 4.57097 \times 10^{-10} \theta_m^{-15} \\
 & -5.87012 \times 10^{-10} \theta_m^{-16} + 4.68978 \times 10^{-10} \theta_m^{-17} \\
 & -2.38145 \times 10^{-10} \theta_m^{-18} + 7.64101 \times 10^{-11} \theta_m^{-19} \\
 & -1.49050 \times 10^{-11} \theta_m^{-20} + 1.60311 \times 10^{-12} \theta_m^{-21} \\
 & \left. -7.24555 \times 10^{-14} \theta_m^{-22} \right] \exp(-12/\theta_m)
 \end{aligned}$$

$$\begin{aligned}
 a(1, 13) = & \left[-6.54407 \times 10^{-13} \theta_m^{-13} + 7.92659 \times 10^{-12} \theta_m^{-14} \right. \\
 & -3.75028 \times 10^{-11} \theta_m^{-15} + 9.41928 \times 10^{-11} \theta_m^{-16} \\
 & -1.41985 \times 10^{-10} \theta_m^{-17} + 1.36452 \times 10^{-10} \theta_m^{-18} \\
 & -8.60316 \times 10^{-11} \theta_m^{-19} + 3.58161 \times 10^{-11} \theta_m^{-20} \\
 & -9.69815 \times 10^{-12} \theta_m^{-21} + 1.63349 \times 10^{-12} \theta_m^{-22} \\
 & \left. -1.54564 \times 10^{-13} \theta_m^{-23} + 6.24250 \times 10^{-15} \theta_m^{-24} \right] \exp(-13/\theta_m)
 \end{aligned}$$

Table 3 (cont.)

$$\begin{aligned}
a(1, 14) = & \left[-9.42926 \times 10^{-14} \theta_m^{-14} + 1.25831 \times 10^{-12} \theta_m^{-15} \right. \\
& -6.64940 \times 10^{-12} \theta_m^{-16} + 1.89268 \times 10^{-11} \theta_m^{-17} \\
& -3.28659 \times 10^{-11} \theta_m^{-18} + 3.70923 \times 10^{-11} \theta_m^{-19} \\
& -2.81253 \times 10^{-11} \theta_m^{-20} + 1.45261 \times 10^{-11} \theta_m^{-21} \\
& -5.09674 \times 10^{-12} \theta_m^{-22} + 1.18953 \times 10^{-12} \theta_m^{-23} \\
& -1.75882 \times 10^{-13} \theta_m^{-24} + 1.48340 \times 10^{-14} \theta_m^{-25} \\
& \left. -5.41002 \times 10^{-16} \theta_m^{-26} \right] \exp(-14/\theta_m)
\end{aligned}$$

$$\begin{aligned}
a(1, 15) = & \left[-1.37214 \times 10^{-14} \theta_m^{-15} + 2.00115 \times 10^{-13} \theta_m^{-16} \right. \\
& -1.16942 \times 10^{-12} \theta_m^{-17} + 3.72665 \times 10^{-12} \theta_m^{-18} \\
& -7.34422 \times 10^{-12} \theta_m^{-19} + 9.55468 \times 10^{-12} \theta_m^{-20} \\
& -8.50849 \times 10^{-12} \theta_m^{-21} + 5.28242 \times 10^{-12} \theta_m^{-22} \\
& -2.29724 \times 10^{-12} \theta_m^{-23} + 6.93829 \times 10^{-13} \theta_m^{-24} \\
& -1.41917 \times 10^{-13} \theta_m^{-25} + 1.86668 \times 10^{-14} \theta_m^{-26} \\
& \left. -1.41847 \times 10^{-15} \theta_m^{-26} + 4.71240 \times 10^{-17} \theta_m^{-28} \right] \exp(-15/\theta_m)
\end{aligned}$$

Table 4

Critical Parameters for Cartesian Geometry ($k = 0$)

θ_m	θ_s^*	δ_m^*	δ_m^* (Ref. 4)	Rel. Dev.
0.50000	0.24459	2.51405	2.51541	0.00054
0.33333	0.21385	2.63346	2.63458	0.00043
0.25000	0.18108	2.69402	2.69504	0.00038
0.20000	0.15523	2.73060	2.73155	0.00035
0.16667	0.13526	2.75508	2.75598	0.00033
0.14286	0.11962	2.77261	2.77348	0.00031
0.12500	0.10712	2.78577	2.78662	0.00030
0.11111	0.09692	2.79603	2.79686	0.00030
0.10000	0.08847	2.80424	2.80506	0.00029
0.09090	0.08136	2.81097	2.81177	0.00029
0.08333	0.07529	2.81657	2.81737	0.00028
0.07692	0.07006	2.82132	2.82210	0.00028
0.07143	0.06550	2.82539	2.82617	0.00028
0.06667	0.06149	2.82892	2.82969	0.00027
0.06250	0.05795	2.83201	2.83277	0.00027
0.05882	0.05479	2.83474	2.83549	0.00027
0.05556	0.05195	2.83716	2.83792	0.00027
0.05263	0.04939	2.83933	2.84008	0.00026
0.05000	0.04708	2.84128	2.84203	0.00026
0.04762	0.04496	2.84305	2.84379	0.00026

Percentage deviation of δ_m^ , by the series method, from the values in Reference 4.

Table 4 (cont.)

θ_m	θ_s^*	δ_m^*	δ_m^* (Ref. 4)	Rel. Dev.
0.04545	0.04303	2.84466	2.84540	0.00026
0.04348	0.04126	2.84612	2.84686	0.00026
0.04167	0.03963	2.84747	2.84820	0.00026
0.04000	0.03812	2.84871	2.84944	0.00026
0.03846	0.03673	2.84985	2.85058	0.00026
0.03704	0.03543	2.85090	2.85163	0.00025
0.03571	0.03422	2.85189	2.85262	0.00025
0.03448	0.03309	2.85281	2.85353	0.00025
0.03333	0.03203	2.85366	2.85438	0.00025
0.03226	0.03103	2.85443	2.85518	0.00026
0.03125	0.03010	2.85519	2.85592	0.00026
0.03030	0.02922	2.85593	2.85663	0.00024
0.02941	0.02839	2.85657	2.85729	0.00025
0.02857	0.02761	2.85720	2.85791	0.00025
0.02778	0.02687	2.85780	2.85850	0.00024
0.02703	0.02617	2.85835	2.85905	0.00025
0.02632	0.02550	2.85888	2.85958	0.00025
0.02564	0.02487	2.85938	2.86008	0.00025
0.02500	0.02426	2.85985	2.86056	0.00025
0.02439	0.02369	2.86031	2.86101	0.00025
0.02381	0.02314	2.86074	2.86144	0.00024

Table 4 (cont.)

θ_m	θ_s^*	δ_m^*	δ_m^* (Ref. 4)	Rel. Dev.
0.02326	0.02262	2.86114	2.86185	0.00025
0.02273	0.02212	2.86155	2.86224	0.00024
0.02222	0.02164	2.86192	2.86262	0.00024
0.02174	0.02118	2.86228	2.86297	0.00024
0.02128	0.02074	2.86262	2.86332	0.00024
0.02083	0.02032	2.86295	2.86365	0.00024
0.02041	0.01992	2.86327	2.86396	0.00024
0.02000	0.01953	2.86357	2.86426	0.00024
0.01961	0.01915	2.86387	2.86455	0.00024

Table 5

Critical Parameters for Cylindrical Geometry ($k = 1$)

θ_m	θ_s^*	δ_m^*	δ_m^* (Ref. 4)	Rel. Dev.
0.50000	0.23811	6.06110	6.06110	0.00000
0.33333	0.20599	6.62980	6.62980	0.00000
0.25000	0.17498	6.94143	6.94143	0.00000
0.20000	0.15061	7.13780	7.13780	0.00000
0.16667	0.13171	7.27280	7.27280	0.00000
0.14286	0.11682	7.37128	7.37128	0.00000
0.12500	0.10486	7.44631	7.44628	0.00000
0.11111	0.09507	7.50554	7.50531	0.00003
0.10000	0.08692	7.55387	7.55297	0.00012
0.09091	0.08005	7.59470	7.59225	0.00032
0.08333	0.07417	7.63093	7.62520	0.00175
0.07692	0.06908	7.66605	7.65321	0.00168
0.07143	0.06465	7.70643	7.67733	0.00379
0.06667	0.06074	7.72520	7.69832	0.00349
0.06250	0.05728	7.74821	7.71674	0.00408
0.05882	0.05419	7.83124	7.73304	0.01270
0.05556	0.05141	7.79371	7.74757	0.00596
0.05263	0.04891	7.74963	7.76060	0.00141
0.05000	0.04663	7.82419	7.77231	0.00668
0.04762	0.04456	7.83430	7.78295	0.00660

Table 5 (cont.)

θ_m	θ_s^*	δ_m^*	δ_m^* (Ref. 4)	Rel. Dev.
0.04545	0.04267	7.83292	7.79264	0.00517
0.04348	0.04092	7.84010	7.80152	0.00485
0.04167	0.03932	7.83999	7.80966	0.00388
0.04000	0.03783	7.84650	7.81715	0.00376
0.03846	0.03646	7.87979	7.82409	0.00712
0.03704	0.03518	9.80751	7.83049	0.25248
0.03571	0.03398	7.70073	7.83653	0.01733
0.03448	0.03287	7.80954	7.84210	0.00415
0.03333	0.03182	7.72565	7.84730	0.01550
0.03226	0.03084	7.70350	7.85216	0.01893
0.03125	0.02992	7.71305	7.85672	0.01829
0.03030	0.02905	7.89245	7.86101	0.00400
0.02941	0.02823	7.70762	7.86506	0.02002
0.02857	0.02746	7.79010	7.86887	0.01001
0.02778	0.02673	7.72857	7.87249	0.01828
0.02703	0.02603	7.68923	7.87589	0.02370
0.02632	0.02537	7.86617	7.87912	0.00165
0.02564	0.02474	7.64780	7.88220	0.02974
0.02500	0.02415	7.75915	7.88511	0.01597
0.02439	0.02358	7.76185	7.88790	0.01598
0.02381	0.02303	6.18600	7.89054	0.21602

Table 5 (cont.)

θ_m	θ_s^*	δ_m	δ_m^* (Ref. 4)	Rel. Dev.
0.02326	0.02252	7.84328	7.89305	0.00631
0.02273	0.02202	7.68725	7.89547	0.02637
0.02222	0.02155	7.69918	7.89778	0.02515
0.02174	0.02109	7.53898	7.89998	0.04570
0.02128	0.02066	7.79101	7.90209	0.01406
0.02083	0.02024	7.51608	7.90411	0.04910
0.02041	0.01984	7.59357	7.90606	0.03953
0.02000	0.01945	8.00098	7.90791	0.01177
0.01961	0.01908	7.59072	7.90971	0.04033

Table 6
Critical Parameters for Spherical Geometry ($k = 2$)

θ_m	θ_s^*	δ_m^*	δ_m^* (Ref. 4)	Rel. Dev.
0.50000	0.23103	10.73846	10.73919	0.00007
0.33333	0.19839	12.25366	12.25458	0.00008
0.25000	0.16900	13.14741	13.14846	0.00008
0.20000	0.14602	13.73569	13.73687	0.00009
0.16667	0.12813	14.14855	14.15324	0.00033
0.14286	0.11397	14.53672	14.46330	0.00508
0.12500	0.10254	14.15495	14.70309	0.03728
0.11111	0.09315	13.37438	14.89409	0.10203
0.10000	0.08531	12.84802	15.04974	0.14630
0.09091	0.07867	12.46574	15.17907	0.17876
0.08333	0.07298	12.17404	15.28823	0.20370
0.07692	0.06805	11.94348	15.38158	0.22352
0.07143	0.06374	11.75634	15.46230	0.23968
0.06667	0.05994	11.60123	15.53283	0.25312
0.06250	0.05657	11.47051	15.59496	0.26447
0.05882	0.05355	11.36321	15.65014	0.27392

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