Fourier series solution to the heat conduction equation with an internal heat source linearly dependent on temperature: Application to chilling of fruit and vegetables

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A R T I C L E   I N F O

Article info:
Article history:
Received 18 December 2007
Received in revised form 26 June 2008
Accepted 27 June 2008
Available online 5 July 2008

Keywords:
Transient heat transfer
Cooling
Heat of respiration
Chilling times

A B S T R A C T

This paper proposes a separation of variables solution to the equation for heat transfer by conduction in simply-shaped, homogeneous and isotropic bodies subjected to cooling or heating processes without a phase change and with an internal heat source that is a linear function of temperature and subject to homogeneous external conditions of the third kind. The solution is given by the sum of an infinite Fourier series. Starting from this solution, the paper also proposes a simple calculation of chilling time based on an approximation to the first term of that solution (exponential zone); it further proposes a first approximation to the maximum value attained by the temperature history, and to the corresponding time.

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1. Introduction

Calculation of heat transfer by conduction through temperature-dependent internal heat sources as in fruits and vegetables, where there are additional problems of geometry, packaging, stowage, respiration heat, etc., is generally a highly complex problem requiring sophisticated numerical procedures only available on a computer. In this context, respiration heat is generally considered to be a function that increases exponentially with temperature (Campanone et al., 2002; Tanner et al., 2002, parts 1 and 2), but various authors use other models in practical cases. For instance, some authors take heat generation to be a constant value (Beek and Meffert, 1981; Dincer, 1994, 1995, 1997; Mendonça et al., 2005; Meffert et al., 1971); then others treat it as a constant in theory but in practice consider it to be negligible in comparison with other more powerful heat sources (Wang et al., 2001). Other authors take a potential model (Sadashive Gowda et al., 1997; and Tanner et al., 2002, parts 1 and 2), or even a function of time (Campanone et al., 2002). There are regression models like those of Kole and Prasad (1994) (regression to a fourth-grade polynomial) or Rao et al. (1993) (regression to a sigmoidal model). Exact analytical solutions have been derived for some particular cases, including heat generation. Jakob (1949), for example, considered the case of conduction with a linear heat source under steady-state conditions, and Carslaw and Jaeger (1959) proposed a solution to the problem in transient conditions for an infinite slab. A solution was also proposed for an infinite cylinder and infinite Biot number.

This study proposes a single general solution based on analysis by separation of variables, which is valid for the three elementary geometries and in a general way for the coefficient of heat transmission.

The reason for adopting a linear rate model for heat generation is that an exact solution is still feasible using separation of variables; moreover, there is an abundance of data in the literature supporting the adoption of such a linear model as a first approximation, for example in Xu and Burfoot (1999), who adopt a linear approach in the case of potato chilling.

Without ruling out other possible applications, the solution proposed here targets the study of cooling of plant foods whose respiratory process constitutes a heat source.

2. Theoretical analysis

The one-dimensional Fourier series for heat transfer in a single dimension, with constant, homogeneous and isotropic coefficients and a linear heat source may be written as

\[ k \frac{1}{r^2} \left( r \frac{\partial T}{\partial r} \right) + A_0 + A_1 \cdot T = \rho c \frac{\partial T}{\partial t} \]

with the boundary condition of the third kind

\[ k \frac{\partial T}{\partial r} \bigg|_{r=R} = -h(T_{int} - T_{out}) \]

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doi:10.1016/j.jfoodeng.2008.06.036
### Nomenclature

- \( A_0 \): constant of the heat source (J m\(^{-3}\) s\(^{-1}\))
- \( A_1 \): slope of the heat source (J m\(^{-3}\) s\(^{-1}\) K\(^{-1}\))
- \( a = \frac{k}{\rho c_p} \): thermal diffusivity (m\(^2\) s\(^{-1}\))
- \( B_0 \): \( A_0 + A_1T_{ex} \) (J m\(^{-3}\) s\(^{-1}\) K\(^{-1}\))
- \( Bi = \frac{hT}{k} \): Biot number
- \( c \): thermal capacity per unit of mass (J kg\(^{-1}\) K\(^{-1}\))
- \( D_0, D_{sw, T} \): displacement corrections dimensionless
- \( F_0 = \frac{\alpha T}{k} \): Fourier number (dimensionless time)
- \( J, J_i \): product of \( J \) multiplied by the average value of \( \psi \)
- \( k \): heat conductivity (W m\(^{-1}\) K\(^{-1}\))
- \( R \): characteristic length (m)
- \( T \): temperature (K)
- \( T_{ex} \): external temperature (K)
- \( T_{sf} \): temperature at surface (K)
- \( \Delta T \): \( T - T_{ex} \) (K)
- \( t \): time (s)
- \( x \): dimensionless distance

### Greek symbols

- \( \alpha^2 = \frac{h_0^2}{k} \): dimensionless slope of the heat source
- \( \beta = \frac{hT}{k} \): dimensionless number of the heat source
- \( \delta = \delta_1 \): first root of the boundary equation
- \( \theta = \frac{\Delta T}{\Delta T_{Th}} \): dimensionless temperature
- \( \theta_{st} \): dimensionless temperature, steady-state solution
- \( \rho \): density (kg m\(^{-3}\))
- \( \varphi \): solution to the time-related part of the equation
- \( \psi \): solution to the spatial part of the equation

\[ \psi' = \frac{\varphi_x}{\psi_x} = \frac{1}{ \frac{\varphi}{\psi} + 1} \]

\( \Gamma \) is the geometric constant taking values \( \Gamma = 0 \) for an infinite slab, \( \Gamma = 1 \) for an infinite cylinder and \( \Gamma = 2 \) for a sphere.

Table 1 shows the values of \( A_0 \) and \( A_1 \) obtained by linear regression of the average values taken from the ASHRAE tables (1998).

The above equations may be written in dimensionless form, thus:

\[ \frac{1}{x^2} \frac{\partial}{\partial x} \left( x^2 \frac{\partial \theta}{\partial x} \right) + x^2 \theta + \beta = \frac{\partial \theta}{\partial F_0} \]

\[ \left[ \frac{\partial \theta}{\partial x} \right]_{x = 1} = -Bi \cdot \theta_{st} \]

where

\[ \theta = \frac{\Delta T}{\Delta T_{Th}} = \frac{T - T_{ex}}{T_{th} - T_{ex}} \]

\[ B_0 = A_0 + A_1 \cdot T_{ex} \]

<table>
<thead>
<tr>
<th>Variety</th>
<th>( A_0 ) (W/kg)</th>
<th>( A_1 ) (W/kg K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apples &quot;Y transparent&quot;</td>
<td>0.0097</td>
<td>0.0073</td>
</tr>
<tr>
<td>Apples average</td>
<td>0.0061</td>
<td>0.0037</td>
</tr>
<tr>
<td>Apples early cultivars</td>
<td>0.0101</td>
<td>0.0040</td>
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<tr>
<td>Apples late cultivars</td>
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<td>0.0025</td>
</tr>
<tr>
<td>Artichokes globe</td>
<td>0.0123</td>
<td>0.0014</td>
</tr>
<tr>
<td>Apricots</td>
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</tr>
<tr>
<td>Asparagus</td>
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<td>0.0478</td>
</tr>
<tr>
<td>Beans lima unshelled</td>
<td>0.0223</td>
<td>0.0211</td>
</tr>
<tr>
<td>Beans lima shelled</td>
<td>0.0303</td>
<td>0.0334</td>
</tr>
<tr>
<td>Beans snap</td>
<td>-0.0153</td>
<td>0.0189</td>
</tr>
<tr>
<td>Beets red roots</td>
<td>0.0160</td>
<td>0.0026</td>
</tr>
<tr>
<td>Black berries</td>
<td>0.0221</td>
<td>0.0213</td>
</tr>
<tr>
<td>Blue berries</td>
<td>0.0028</td>
<td>0.0097</td>
</tr>
<tr>
<td>Broccoli</td>
<td>0.0229</td>
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<td>Brussels sprouts</td>
<td>0.0436</td>
<td>0.0179</td>
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<td>Cabbage pennis state</td>
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<td>Cabbage red early</td>
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<td>Cabbage savoy</td>
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<td>Cabbage white spring</td>
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<td>Cabbage white winter</td>
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<td>Cauliflower</td>
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<td>0.0117</td>
</tr>
<tr>
<td>Celery</td>
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<td>0.0060</td>
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<tr>
<td>Gooseberries</td>
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</tr>
<tr>
<td>Peas green</td>
<td>0.0486</td>
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<td>Potatoes(^*)</td>
<td>0.0154</td>
<td>0.0019</td>
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<tr>
<td>Raspberries</td>
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</tr>
<tr>
<td>Strawberries</td>
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<td>0.0213</td>
</tr>
</tbody>
</table>

\(^*\) From Xu and Burfoot (1999).

3. General solution for simple geometries

Eq. (1) has to be integrated with the boundary condition (2). Denominating the steady state as \( \theta_e \), the general solution may be written as follows (see Appendix 1):

\[ \theta(x, \Gamma) - \theta_e = \sum_i \left( J_i(\delta(x)) \cdot e^{-i\delta_1^2 - \delta_2^2} \right) \]

The steady solution \( \theta_e \) is (see Appendix 2):

\[ \theta_e = \frac{T_s - T_{ex}}{\Delta T_{Th}} = \frac{\beta}{\frac{\beta}{\varphi_{s, 2}^2} - 1} \frac{1}{\frac{\beta}{\varphi_{s, 2}^2} - \frac{\beta}{\varphi_{s, 1}^2}} \]

\( \delta_1 \) is the solution to the classical transcendental equation [as in the no heat generation case]:

\[ \delta \cdot \psi'(\delta) = -Bi \cdot \psi(\delta) \]

and coefficients \( J_i \) (see Appendix 3):

\[ J_i = J_{i, 0} \left( 1 - \frac{\beta}{\delta_1^2 - \delta_2^2} \right) \]

where \( J_{i, 0} \) is the coefficient in the absence of heat generation:

\[ J_{i, 0} = \frac{2Bi}{\psi_{s, 2}^2 + Bi^2 - (\Gamma - 1)Bi} \]

and the function \( \psi \) has the following expressions:

\[ \psi(\delta(x)) = \cos(\delta_1 \chi); \psi(\delta(x)) = \cos(\delta_2 \chi) \] for an infinite slab

\[ \psi(\delta(x)) = \frac{J_{i, 0}(\delta(x))}{\psi_{s, 2}}; \psi(\delta(x)) = \frac{J_{i, 0}(\delta(x))}{\psi_{s, 1}} \] for an infinite cylinder

\[ \psi(\delta(x)) = \frac{\sin(\delta_1 \chi)}{\delta_1^2 \chi^2}; \psi(\delta(x)) = \frac{\sin(\delta_2 \chi)}{\delta_2^2 \chi^2} \] for a sphere
Therefore, the temperature function becomes
\[
\theta = \frac{T - T_{\text{ex}}}{\Delta T_0} = \frac{\beta}{2} \left( \frac{B_i \cdot \psi(x)}{x \psi_2 + B_i \psi_1} - 1 \right) + \sum_J J_i \psi(\delta x) e^{- (\delta x^2)} f_0 \quad (6)
\]

4. Threshold Biot number

As shown in Appendix 2, \( \delta x^2 \) must satisfy the condition:
\[
\delta x^2 < \delta_{\text{th}}^2 < \delta_0^2 \quad (7)
\]
Also, given that in most fruits and vegetables the value of \( \delta x^2 \) is in the region of \( 10^{-2} \), an approximate value can be found for this threshold Biot number. The first value of \( \delta_{\text{th}}^2 \) may be approximated in elementary geometries for Biot numbers close to zero (Cuesta and Lamúa, 1995) with the equation (to facilitate writing, when working exclusively with the first term of the series we drop subscript 1, which denotes the order number, and the function’s argument whenever there is no room for doubts):
\[
\frac{1}{\delta^2} = \frac{1}{2(1 + 1)} \left( 1 - \frac{2}{B_i} \right)
\]
From this equation and relationship (7) we can deduce:
\[
B_i \geq \frac{2\delta^2}{2(1 + 1) - \delta^2} \quad (8)
\]
And, when the value of \( \delta x^2 \) is very small, this is reduced to
\[
B_i \geq \frac{\delta^2}{1 + 1} \quad (9)
\]
5. Average value

The mass average temperature of the product at constant density is as follows (see Appendix 4):
\[
\bar{\theta} = \bar{\theta}_s + \sum_J \tilde{J}_i \cdot e^{- (\delta x^2)} f_0 \quad (10)
\]
with \( \tilde{J}_i = J_i \cdot \left( 1 - \frac{\beta}{2\delta_x} \right) \) and
\[
\tilde{J}_{i0} = J_{i0} \cdot \psi_i = \frac{2B_i^2 (1 + 1)}{\delta_{\text{th}}^2 [\delta_{\text{th}}^2 + B_i^2 - (1 - 1)B_i]}
\]
Therefore, the mass average temperature function becomes
\[
\bar{\theta} = \frac{\bar{T} - T_{\text{ex}}}{\Delta T_0} = -\frac{\beta}{2\delta_x} \left[ \left( 1 + 1 \right) \frac{B_i \psi_1}{x \psi_2 + B_i \psi_1} + 1 \right] + \sum_J \tilde{J}_i \cdot e^{- (\delta x^2)} f_0 \quad (11)
\]
6. Chilling times

As in the case of chilling without an internal heat source, when the time is long enough the calculation can be done with the first term of the series. In this case Eq. (5) may be rewritten approximately as follows:
\[
Y = \bar{\theta} - \theta_s(x) \approx J_1 \psi e^{- (\delta x^2)} f_0 \quad (12)
\]
If the subscript \( c \) denotes the values at the thermal core:
\[
Y_c = J_1 \psi e^{- (\delta x^2)} f_0
\]
we have
\[
Y = Y_c \psi
\]
Similar to the case with no internal source, chilling times for sufficiently large Fourier numbers can be calculated using a very simple linear analytical expression. Thus, from the exponential Eq. (12):
\[
\ln Y = \ln(J\psi) - (\delta^2 - \delta^2) \cdot F_c
\]
and the Fourier number (dimensionless time) can immediately be found:
\[
F_c = \frac{\ln(J\psi)}{\delta^2 - \delta^2} \quad (13)
\]
In the cases of the thermal core and average value these equation will be
\[
F_c = \ln(J\psi)/\delta^2 - \delta^2
\]
And for the mass average value:
\[
F_0 = \frac{\ln(J\psi)}{\delta^2 - \delta^2}
\]
7. Displacement correction

Eq. (13) can be rewritten as
\[
F_0 = \frac{\ln(J\psi)}{\delta^2 - \delta^2} = \frac{\ln(J\psi)}{\delta^2 - \delta^2} + \ln(1/\delta)
\]
The first term is the value of the Fourier number corresponding to the core \( F_{oc} \), and the second term represents the increase in that number due to displacement to the x coordinate.
\[
F_0 = F_{oc} + \ln(1/\delta) = F_{oc} - \ln(1/\psi)
\]
\[
F_{oc} = F_{oc} - D_s
\]
with
\[
D_s = \frac{\ln(1/\psi)}{\delta^2 - \delta^2}
\]
Clearly this term is dependent not on time but solely on the coordinate. Hence, other than for low Fourier numbers, if we wish to calculate the time required at a coordinate \( x \) to reach a given temperature \( \bar{\theta} \), it will suffice to know the time needed to calculate it at the core and adjust this with the appropriate term for displacement. In the particular cases of the surface and the average value we get:
\[
\text{(A) Surface:}
D_s = \frac{\ln(1/\psi)}{\delta^2 - \delta^2}
\]
\[
\text{(B) Average value:}
D_s = \frac{\ln(1/\psi)}{\delta^2 - \delta^2}
\]
8. Summary of the procedure

Hence, in the exponential zone (where the first term is enough), if we wish to know the time \( F_0 \) needed to attain the absolute dimensionless difference \( \bar{\theta} \), it will suffice to apply the following procedure:

(i) Take the difference value: \( Y = \bar{\theta} - \theta_s \)
(ii) Calculate the time for the core (Eq. (14))
\[
F_{oc} = \frac{\ln(J\psi)}{\delta^2 - \delta^2}
\]
(iii) Carry out the appropriate displacement if applicable (Eq. (16) or (17)):

\[ D_x = \frac{\ln(1/\psi)}{\delta^2 - \alpha^2} \]

and finally import to (15)

\[ F_{oY} = F_{oY} - D_x \]

9. Illustrative example

Let us take the case of an individual potato which we wish to cool from 25 °C to 5 °C. According to Xu and Burfoot (1999), we may assume that this potato is like a sphere 0.065 m in diameter (that is, \( r + 1 = 3 \)) with respiration heat rising linearly with temperature

\[ q_r = A_0 + A_1 T \]

where the parameters \( A_0 \) and \( A_1 \), as previously stated in SI units, are \( A_0 = 0.01739 \text{ W/kg} \) and \( A_1 = 0.001942 \text{ W/kg K} \).

Since the parameters \( A_0 \) and \( A_1 \) in this work are measured in:

\[ |A_0| = \text{W/m}^3 \text{ and } |A_1| = \text{W/m}^3 \text{ K} \]

the first two will have to be multiplied by the density to get the last two. Table 3 in ASHRAE (1998) gives us the following components for potato:

\[ \begin{align*}
    x_{\text{water}} &= 0.79; \quad x_{\text{rot}} = 0.0207; \quad x_{\text{fat}} = 0.001; \\
    x_{\text{carboh}} &= 0.1798; \quad x_{\text{frih}} = 0.0089
\end{align*} \]

From these, taking the equations in Tables 1 and 2 as reference, we get the following values for the thermophysical parameters:

\[ \rho = 1123.5 \text{ kg/m}^3, \quad k = 0.485 \text{ W m}^{-1} \text{ K}^{-1}, \quad a = 0.1253 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}, \quad c_p = 3636.6 \text{ J kg}^{-1} \text{ K}^{-1} \]

so that the respective values of \( A_0 \) and \( A_1 \) are finally:

\[ \begin{align*}
    A_0 &= 0.01739 \times 1123.5 = 19.54 \text{ W/m}^3 \\
    A_1 &= 0.001942 \times 1123.5 = 2.18 \text{ W/m}^3 \text{ K}
\end{align*} \]

With this and the conductivity value deduced previously, it is possible to calculate the dimensionless parameters \( x^2 \) and \( \beta \) (Eqs. (3) and (4)); \( x^2 = \frac{2.1816 \times 10^{-6} \text{ W m}^2 \text{ K}}{0.00475} = 0.00475 \) whose value depends solely on the specific fruit and not on the process. The external temperature is 5 °C and the total temperature difference is \( \Delta T_0 = 25 - 5 = 20 \text{ °C} \). So, the value of \( \beta \) will be

\[ \beta = \frac{B_0 \cdot R^2}{k \cdot \Delta T_0} = \frac{(A_0 + A_1 T_m) \cdot R^2}{k \cdot T_0} = \frac{30.45 \times 0.0325^2}{0.4854 \times 20} = 0.00331 \]

which depends both on the potato itself and on the cooling/heating process, since it is affected by the external temperature and the total temperature difference.

Since this is only an illustrative example, we shall further assume that cooling takes place with an air velocity such that the value of the Biot number is \( Bi = 0.2 \); the corresponding value of \( \delta = 0.7593 \), and hence \( \delta^2 = 0.5765 \), which is greater than the value calculated previously for \( x^2 \). Thus the condition is satisfied.

The parameter \( J_0 \) corresponding to the Biot number \( Bi = 0.2 \) is \( J_0 = 1.0592 \).

Hence

\[ J = J_0 \left( 1 - \frac{\beta}{\delta^2 - \alpha^2} \right) = 1.0592\left( 1 - \frac{0.00331}{0.5765 - 0.00475} \right) = 1.0531 \]

The steady temperature at the core is

\[ \theta_s(0) = \frac{Bi}{2x} \left[ \frac{1}{\alpha^2} + \frac{1}{\beta^2} \right] - 1 = 0.0061 \]

The displacement of \( Fo \) on the surface will be

\[ D_{sy} = -\frac{\ln(\frac{\ln(\frac{1}{\psi})}{\delta^2 - \alpha^2})}{\delta^2 - \alpha^2} = 0.1714 \]

and the displacement for the average value:

\[ D_{av} = -\frac{\ln(\frac{\ln(\frac{1}{\psi})}{\delta^2 - \alpha^2})}{\delta^2 - \alpha^2} = 0.1714 - \frac{\ln(\frac{2 + 0.2}{\delta^2 - \alpha^2})}{(0.5765 - 0.00475)} = 0.1017 \]

If we take \( Y = 1/2 \) as the reference for the core, the half-cooling time will be

\[ F_{oY} = F_{oY} - D_{sy} = 1.3026 \]

Let us imagine that we wish to attain the absolute dimensionless temperature \( \theta = 0.3 \). This means that

\[ Y_{a3} = 0 = \theta_s - 0.3 = 0.0061 = 0.2939 \]

and hence the dimensionless time required to attain the dimensionless temperature \( \theta = 0.3 \) at the core is

\[ F_{oY} = F_{oY} - D_{sy} = 1.3026 - \frac{\ln(2 + 0.2939)}{(0.5765 - 0.00475)} = 2.2320 \]

which coincides with the value derived using the entire series.

As we have seen, the term of displacement to the surface is

\[ D_{sy} = 0.1714 \]

and hence the dimensionless time needed to attain \( \theta = 0.3 \) at the surface is

\[ D_{av} = F_{oY} - D_{sy} = 2.2320 - 0.1714 = 2.0606 \]

The value produced by the complete series is

\[ F_{oY} = 2.0575 \]

Therefore, the error is 0.15%.

As we have seen, the average value of its displacement is

\[ D_{av} = 0.1017 \]

Therefore, the time needed to attain the average value \( \theta = 0.3 \) will be

\[ F_{oY} = F_{oY} - D_{av} = 2.2320 - 0.1017 = 2.1303 \]

The value of the complete series is \( F_{oY} = 2.1284 \), and therefore the error is 0.09%.

The values for this example in the case when there is no respiration are

Core: \( F_{oY} = 2.1879 \) (difference -1.98%)

Surface: \( F_{oY} = 2.0079 \) (difference -2.47%)

Average value: \( F_{oY} = 2.0770 \) (difference -2.41%)

That is, in this particular case because the values of \( A_0 \) and \( A_1 \) are low, the mass considered is small (an individual potato) and the Biot number is much larger than the threshold value, the influence of the respiration heat is relatively small.
Figs. 1 and 2 illustrate the influence of the parameters $a^2$ and $b$ by plotting the temperature history for a fixed Biot number ($Bi = 5$) and for different values of $a^2$ and $b$. In Fig. 1 the value of $b$ ($b = 1$) is fixed and that of $a^2$ varies between $a^2 = 1$ and $a^2 = 5$ (always lower than the first value of $a^2$ corresponding to the Biot number), while in Fig. 2 $a$ is fixed ($a^2 = 1$) and $b$ varies between $b = 1$ and $b = 5$.

By way of illustration, Fig. 3 depicts the temperature history for the three elementary geometries for the values $Bi = 5$, $a^2 = 0.5$ and $b = 0.5$.

10. Approximation to maximum value at the core

As we can see in both figures, depending on the particular conditions in each case the temperature may rise at the outset up to a given maximum value $\theta_M$ in a time $Fo_M$, falling thereafter down to its steady value. A first approximation to this value can be achieved by considering that its time derivative must also vanish. Hence, at this point the following condition is required:

$$\left. \frac{dY}{dFo} \right|_{Fo_M} = - \sum \left( \delta_i^2 - x^2 \right) Y_i \psi(\delta_x) \cdot e^{-(\delta_i^2-x^2)Fo_M} = 0$$

To calculate a first approximation to this value, the first two terms of the series can be taken as significant:

$$\left. \frac{dY}{dFo} \right|_{Fo_M} \approx -(\delta_1^2 - x^2) Y_1 \psi(\delta_1x) \cdot e^{-(\delta_1^2-x^2)Fo_M} - (\delta_2^2 - x^2) Y_2 \psi(\delta_2x) \cdot e^{-(\delta_2^2-x^2)Fo_M} = 0$$

Specifically, at the core $\psi = 1$, which leaves:

$$\left. \frac{dY}{dFo} \right|_{Fo_M} \approx -(\delta_1^2 - x^2) Y_1 \cdot e^{-(\delta_1^2-x^2)Fo_M} - (\delta_2^2 - x^2) Y_2 \cdot e^{-(\delta_2^2-x^2)Fo_M} = 0$$

and from this we can find the value of $Fo_M$:

$$Fo_M \approx \left[ \frac{\delta_2^2 - x^2}{\delta_1^2 - x^2} \right]$$

If we substitute this value in the sum of the first two terms of the series, we get an approximation to the maximum value attained

$$\theta_M \approx \theta_0, \theta_1 + Y_1 \cdot e^{-(\delta_1^2-x^2)Fo_M} + Y_2 \cdot e^{-(\delta_2^2-x^2)Fo_M}$$
shows the corresponding maximum values attained by \( h \) calculated with Eq. (19). Both tables also show the values derived calculated with Eq. (18) for the cases depicted in Fig. 1, and Table 3 using the complete series and the differences expressed in \%. 

**Table 2** shows the maximum values of the Fourier number \( (Fo_M) \) calculated with Eq. (18) for the cases depicted in Fig. 1, and Table 3 shows the corresponding maximum values attained by \( (\theta_M) \) calculated with Eq. (19). Both tables also show the values derived using the complete series and the differences expressed in \%.

**11. Conclusions**

1. This paper describes the analytical Fourier series solution to the equation for heat transfer by conduction in simple geometries with an internal heat source linearly dependent on temperature.

2. The threshold condition for chilling is established.

3. A simple method based on the first term is proposed for calculation of chilling times at the core, mass average and surface.

4. Two simple equations are proposed for approximate calculation of the maximum temperature value attained at the core, and also the corresponding time.

**Appendix 1. General solution**

Eq. (A1-1) is to be integrated

\[
\frac{1}{x^2} \left( x^2 \frac{\partial \theta}{\partial x} \right) + x^2 \theta + \beta = \frac{\partial \theta}{\partial Fo}
\]

(A1-1)

with the boundary condition (A1-2):

\[
\left[ \frac{\partial \theta}{\partial x} \right]_{x=1} = -Bi \cdot \theta_{st}
\]

(A1-2)

By definition the steady-state solution does not depend on time, and therefore the second term of Eq. (A1-1) is cancelled when applied to that case. If we mark the steady-state function with subscript „s”, we get

\[
1 \frac{\partial}{\partial x} \left( x^2 \frac{\partial \theta_s}{\partial x} \right) + x^2 \theta_s + \beta = \frac{\partial \theta_s}{\partial Fo}
\]

(A1-3)

\[
\left[ \frac{\partial \theta_s}{\partial x} \right]_{x=1} = -Bi \cdot (\theta_s)_{st}
\]

(A1-4)

where

\[ \theta_s = \frac{T_s - T_{ex}}{T_0 - T_{ex}} \]

If we subtract Eqs. (A1-3) and (A1-4) from Eqs. (A1-1) and (A1-2), respectively, this leaves:

\[
1 \frac{\partial}{\partial x} \left( x^2 \frac{\partial (\theta - \theta_s)}{\partial x} \right) + x^2 (\theta - \theta_s) = \frac{\partial (\theta - \theta_s)}{\partial Fo}
\]

(A1-5)

\[
\left[ \frac{\partial (\theta - \theta_s)}{\partial x} \right]_{x=1} = -Bi \cdot (\theta - \theta_s)_{st}
\]

(A1-6)

(A1-5) admits a solution in separation of variables in the same way as without a heat source. The complete solution will therefore be a serial expansion in the form:

\[
\theta(x, Fo) = \theta_s(x) + \sum_{i=1}^{\infty} J_i \cdot \psi(\delta x) \cdot e^{-x^2 \cdot \gamma^i \cdot Fo}
\]

(A1-7)

where \( \delta \) are the infinite solutions of the boundary equation:

\[
\delta \cdot \psi'(\delta) = -Bi \cdot \psi(\delta)
\]

and where (see Appendix 2) if \( x^2 > 0 \):

\[
\theta_s = \frac{\beta}{2x} \left[ \frac{Bi \psi(x)}{2xy_x^2 + Bi \psi_x} - 1 \right]
\]

(A1-8)

The \( J_i \) constants can be written as follows (see Appendix 3):

\[
J_i = J_{i,0} \left( 1 - \frac{\beta}{\delta_i^2 - x^2} \right)
\]

(A1-9)

where the values \( J_{i,0} \) are the constants of the serial expansion for the case with no heat source.
particular solution of (A2-1) is

\[ \frac{2Bi}{\psi_i(\alpha^2 + Bi^2 - (\alpha - 1)Bi)} \]  

**Appendix 2. Steady-state**

Eq. (A1-7) will be the desired solution if the function \( \psi_x \) corresponding to \( Fo = \infty \) is known, for which it is necessary to solve the equation:

\[
\frac{1}{R^2} \frac{\partial}{\partial x} \left( R^2 \frac{\partial \psi_x}{\partial x} \right) + x^2 \psi_x + \beta = 0 \tag{A2-1}
\]

with the transcendental equation:

\[
\left[ \frac{\partial \psi_x}{\partial x} \right]_{x=1} = -Bi \cdot (\psi_x)_x \tag{A2-2}
\]

where

\[
\psi_x = \frac{T_x - T_{in}}{T_0 - T_{in}} \tag{A2-3}
\]

The homogeneous differential equation corresponding to (A2-1) will be

\[
\frac{1}{R^2} \frac{\partial}{\partial x} \left( R^2 \frac{\partial \psi_x}{\partial x} \right) + x^2 \psi_x = 0 \tag{A2-4}
\]

As the constant source case \((A_0 > 0 \text{ and } A_1 = 0)\) was considered by Beek and Meffert, in this paper we consider only the case where \(x^2 > 0\). In this case the solution is the same as in the case with no heat source, except that here the coefficient \(x^2\) is imposed by the product’s internal heat source and hence is unique. In this case a particular solution of (A2-1) is

\[
\psi_x = -\frac{\beta}{\alpha^2} \tag{A2-5}
\]

The steady solution is then equal to

\[
\psi_x = M \psi(\alpha x) - \frac{\beta}{\alpha^2} \tag{A2-5}
\]

So that (A2-1) will be satisfied except for the constant M. Hereafter, as long as there is no risk of confusion, we will use the notation:

\[
\psi_x \equiv \psi(\alpha x) \quad \psi_x^* \equiv \psi(\alpha) = [\psi(\alpha x)/\psi(\alpha)]
\]

To derive the constant M, (A2-5) is substituted in the boundary condition (A2-2). After rearranging terms this leads to

\[
M = \frac{Bi \cdot \beta}{x^2 [x \psi_x^* + Bi \psi_x^*]} \tag{A2-6}
\]

If Eq. (A2-6) is substituted in (A2-5) we have

\[
\psi_x = \frac{\beta}{\alpha^2} \left[ \frac{Bi \psi(\alpha x)}{x \psi_x^* + Bi \psi_x^*} - 1 \right] \tag{A2-7}
\]

which is the same expression as found by Jakob (1949) for the same particular case in each of the three elementary geometries.

Following the reasoning of Jakob (1949), at this point we can state that the conditions that Eq. (6) must meet to remain positive are

\[
Bi \cdot \psi(\alpha x) \geq x \psi_x^* + Bi \psi_x^* \quad \text{and} \quad x \psi_x^* + Bi \psi_x^* \geq 0
\]

The first relationship can also be written as

\[
Bi \cdot [\psi(\alpha x) - \psi(\alpha)] \geq x \psi(\alpha) \tag{A2-8}
\]

This is always true, since the left hand side of Eq. (A2-8) is always positive or null, whereas the right hand side is always null or negative. In fact \(\psi(\alpha x) > \psi(\alpha)\) given that because \(0 < \alpha < 1\), \(\alpha x < \alpha \) (e.g. in the case of a flat slab \(cos \alpha > cos x\)), and hence the left hand side of Eq. (A2-8) is always positive or null. And within this range \(\psi(\alpha x) \) (in the infinite slab case \(-sin \alpha\)) and so the right hand side is always \(0\).

The second relationship indicates that there is a lower threshold Biot number for each value of \(\alpha\), so that the Biot number must satisfy the condition:

\[
Bi \geq \frac{-2 \psi(\alpha)}{\psi(\alpha)} \tag{A2-8}
\]

At the same time, the transcendental equation for the general case is

\[
\frac{-\delta \psi(\alpha)}{\psi(\alpha)} = \frac{-2 x \psi(\alpha)}{\psi(\alpha)}
\]

so that

\[
Bi = \frac{-\delta \psi(\alpha)}{\psi(\alpha)} \tag{A2-8}
\]

In other words:

\[
-\frac{\delta \psi(\alpha)}{\psi(\alpha)} \geq -2 x \psi(\alpha)
\]

Since the general function

\[
y = \frac{-x \psi(\alpha)}{\psi(\alpha)}
\]

is continuous and monotonously positive within the range \(0 < x < \delta_M\) for all three elementary geometries, this condition is only fulfilled if:

\[
\alpha \geq \delta
\]

which for convenience will be expressed in the form:

\[
ax^2 \leq \delta^2 \tag{A2-9}
\]

and obviously \(\delta\) will always be less than its maximum value \(\delta_M\) (for an infinite Biot number):

\[
\delta^2 \leq \delta_M^2
\]

So, the conditions are finally:

\[
ax^2 \leq \delta^2 \leq \delta_M^2
\]

Thus, as the Biot number decreases, \(x\) approaches \(\delta\) and the denominator \(x \psi_x^* + Bi \psi_x^*\) will approach \(\delta \psi_x^* + Bi \psi_x^*\), which is zero, and therefore in the limit case \(x \psi_x^* + Bi \psi_x^* = 0\), \(\theta_x = 0\) and hence also Eq. (6) for \(\theta\) will tend towards infinity. Following both Jakob’s (1949) and Carslaw’s (1959) reasoning, all this means that in such a hypothetical case, extraction of heat via the surface would not be sufficient to eliminate the heat generated in the interior and the temperature rise would be unbounded.

**Appendix 3. Core: deducing the expansion constants**

At the starting point \((Fo = 0)\) the solution may be written as

\[
0(\alpha, 0) - 0(\alpha, \beta) = 00 - 01 = \sum J_l \psi(\alpha x) \tag{A3-1}
\]

where (see Appendix 2, Eq. (A2-5))

\[
\psi_x = M \cdot \psi(\alpha x) - \frac{\beta}{\alpha^2} \tag{A3-2}
\]

and
\[ M = \frac{\frac{B_i \cdot \beta}{x^2} \left[ \psi_x + Bi \psi_x \right]}{x^2} \]  
(A3-3)

may be written as
\[ M(\frac{\psi_x}{x^2} + Bi \psi_x) = \frac{B_i \cdot \beta}{x^2} \]  
(A3-4)

To calculate the coefficients \( j_i \), we multiply both sides of Eq. (A3-1)
by \( x^2 \psi(\delta x) \) and integrate between \( x = 0 \) and \( x = 1 \). This gives
\[ \int_0^1 (\theta_0 - \theta_0 x^2) x^2 \psi(\delta x) dx = \int_0^1 x^2 \psi(\delta x) \psi(\delta x) dx \]
For two solutions \( \delta_i \) and \( \delta_j \) corresponding to the same Biot number, the following two integral orthogonality properties are deduced:
\[ \delta_i \neq \delta_j; \int_0^1 x^2 \cdot \psi(\delta_i) \cdot \psi(\delta_j) \cdot dx = 0 \]
\[ \delta_i = \delta_j; \int_0^1 x^2 \cdot \psi^2(\delta_i) \cdot dx = \frac{\psi^2(\delta_i)}{2\delta_i} \]
So that
\[ j_i = \frac{\int_0^1 (\theta_0 - \theta_0 x^2) x^2 \psi(\delta_i) dx}{\int_0^1 x^2 \psi(\delta_i) \psi(\delta_i) dx} = \frac{\frac{B_i}{2\delta_i}}{\frac{\psi^2(\delta_i)}{2\delta_i} + Bi^2 + (1 - 1) \cdot Bi} \]  
(A3-5)

As \( \theta_0 x = 1 = cte \)
we have, by substituting (A3-2)
\[ j_i = \frac{(1 + \frac{\beta}{x^2}) \int_0^1 x^2 \psi(\delta_i) dx}{\frac{\psi^2(\delta_i)}{2\delta_i} + Bi^2 + (1 - 1) \cdot Bi} - \frac{M \int_0^1 x^2 \psi(\delta_i) \psi(\delta_i) dx}{\frac{\psi^2(\delta_i)}{2\delta_i} + Bi^2 + (1 - 1) \cdot Bi} \]

The first term in the right hand side contains the \( j_i \) coefficient for the case without internal heat sources (Cuesta et al., 1990):
\[ j_{i,0} = \frac{\frac{B_i}{2\delta_i}}{\frac{\psi^2(\delta_i)}{2\delta_i} + Bi^2 + (1 - 1) \cdot Bi} \]  
(A3-6)

so that \( j_i \) may be written:
\[ j_i = \left(1 + \frac{\beta}{x^2}\right) j_{i,0} - \frac{M \int j_{i,0} x^2 \psi(\delta_i) \psi(\delta_i) dx}{\frac{\psi^2(\delta_i)}{2\delta_i} + Bi^2 + (1 - 1) \cdot Bi} \]  
(A3-7)

If we solve the integral of the numerator of the second term (considering the boundary condition \( \psi_{\delta_i} = -Bi \psi_{\delta_i} \)) and Eq. (A3-4) and rearrange this terms, this gives
\[ j_i = \left(1 + \frac{\beta}{x^2}\right) j_{i,0} + \frac{2Bi}{x^2 - \delta_i^2} \psi_{\delta_i} \left[ \frac{\psi^2(\delta_i)}{2\delta_i} + Bi^2 + (1 - 1) \cdot Bi \right] \]
Taking (A3-6) into account, we have
\[ j_i = j_{i,0} \left(1 - \frac{\beta}{\delta_i^2 - \frac{x^2}{2}}\right) \]  
(A3-8)

**Appendix 4. Average temperature: deducing the expansion constants**

In simple geometries, the mass average temperature of the product is calculated according to the expression:
\[ \theta = (\Gamma + 1) \int_0^1 x^2 \theta(x, Fo) dx \]  
(A4-1)

\( \theta \) may be written as
\[ \theta = \theta_0 + \sum j_i \psi_i(\delta x) e^{-(\delta_i^2 - x^2)Fo} \]
and therefore
\[ \tilde{\theta} = \theta_0 + \sum j_i \psi_i(\delta x) e^{-(\delta_i^2 - x^2)Fo} \]
which again is composed of two terms. The first corresponds to the average steady temperature:
\[ \overline{\psi}_e = (\Gamma + 1) \int_0^1 x^2 \cdot \theta_0(x) dx \]  
(A4-2)

and the second formally corresponds to the average value for the case with no respiration, except that the coefficients \( j_i \) is now given by equation (A3-12). Hence, the average value of \( \psi(\delta_i) \), \( \psi_{\delta_i} \), will be
\[ \tilde{\psi} = \frac{(\Gamma + 1) \psi_{\delta_i}}{\delta_i} = \frac{(\Gamma + 1)Bi \psi_{\delta_i}}{\delta_i} \]  
(A4-3)

so that, for \( \overline{\theta}_0 = 1 \), the products \( j_i = j_i \psi_{\delta_i} \) become:
\[ j_i = j_{i,0} \cdot \left(1 - \frac{\beta}{\delta_i^2 - \frac{x^2}{2}}\right) \]  
(A4-4)

\( j_{i,0} = j_{i,0} \cdot \psi_{\delta_i} = \frac{2Bi(\Gamma + 1)}{\delta_i^2 + Bi^2 - (1 - 1)Bi} \]  
(A4-5)

As to the average steady value:
\[ \overline{\psi}_s = (\Gamma + 1) \int_0^1 x^2 \cdot \theta_0 dx = (\Gamma + 1) \int_0^1 x^2 \cdot \left[ M(\psi(\delta x) - \frac{\beta}{\delta x^2}) dx \right] \]
\[ \overline{\psi}_s = M(\Gamma + 1) \int_0^1 x^2 \cdot \psi(\delta x) dx - (\Gamma + 1) \frac{\beta}{\delta x^2} \int_0^1 x^2 dx = I_1 - I_2 \]

which can be shown to have the following solutions:
\[ I_1 = -\frac{M(\Gamma + 1)}{\delta x^2} \psi_{\delta x} \]
\[ I_2 = (\Gamma + 1) \frac{\beta}{\delta x^2} \int_0^1 x^2 dx = \frac{\beta}{\delta x^2} \]

and hence
\[ \overline{\psi}_s = I_1 - I_2 = -\frac{M(\Gamma + 1)}{\delta x^2} \psi_{\delta x} - \frac{\beta}{\delta x^2} \]  
(A4-6)

and if we introduce (A2-6)
\[ \overline{\psi}_s = \frac{\beta}{\delta x^2} \left[ \psi(\delta x) + Bi \psi_{\delta x} + 1 \right] \]  
(A4-7)

Thus, the average temperature is
\[ \tilde{\theta} = \overline{\theta}_0 + \sum j_i \cdot e^{-(\delta_i^2 - x^2)Fo} \]

That is
\[ \tilde{\theta} = \frac{T - T_{ex}}{\Delta T_0} \]
\[ = -\frac{\beta}{\delta x^2} \left(\psi_{\delta x} + Bi \psi_{\delta x} + 1 \right) + \sum j_i \cdot e^{-(\delta_i^2 - x^2)Fo} \]  
(A4-8)

with
\[ j_i = j_{i,0} \cdot \left(1 - \frac{\beta}{\delta_i^2 - \frac{x^2}{2}}\right) \]
and
\[ j_{i,0} = j_{i,0} \cdot \psi_{\delta_i} = \frac{2Bi(\Gamma + 1)}{\delta_i^2 + Bi^2 - (1 - 1)Bi} \]
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