Level IIa: $(T_0 - T_1)g(t) \gg \mathbf{O}\left[\frac{L^2}{\alpha}\left(\frac{\partial T}{\partial t}\right)\right]$ (46a)

Level IIb: $(T_0 - T_1)g(t) \gg \mathbf{O}\left[\frac{L^2}{k}\left(\frac{\partial k}{\partial T}\right)\left(\frac{\partial T}{\partial x}\right)^2\right]$ (46b)

Here we are beginning to see how "long" one must wait before the solution becomes quasi-steady, and how "small" the variation of the thermal conductivity must be in order that the last term in Eq. (30) can be discarded.

In order to proceed further, we must be willing to estimate the derivatives that appear in Eqs. (46a,b), and in this development we will be satisfied with the rather crude estimates given by [2, Sec. 2.9].

$$\frac{\partial T}{\partial t} = \mathbf{O}\left[\frac{T|_{x=0} - T|_{x=L}}{t}\right] = \mathbf{O}\left[\frac{(T_0 - T_1)g(t)}{t}\right], \quad t \geq t^* \tag{47a}$$

$$\frac{\partial T}{\partial x} = \mathbf{O}\left[\frac{T|_{x=0} - T|_{x=L}}{L}\right] = \mathbf{O}\left[\frac{(T_0 - T_1)g(t)}{L}\right] \tag{47b}$$

This aspect of the problem could be considered more carefully by introducing the thermal boundary layer thickness; however, we are interested in knowing under what circumstances Eq. (44) is valid and the estimates given by Eqs. (47a,b) are consistent with that objective. When Eqs. (47a,b) are used in Eqs. (46a,b) we obtain the Level III constraints given by

Level IIIa: $\frac{\alpha t}{L^2} \gg 1, \quad t \geq t^*$ (48a)

Level IIIb: $\frac{1}{k}\left(\frac{\partial k}{\partial T}\right)(T_0 - T_1)g(t) \ll 1$ (48b)

The first of these clearly indicates that the process will be quasi-steady when t^* is large compared to L^2/α and an exact solution of the boundary value problem will indicate that this is a conservative constraint. Since $g(t)$ has an upperbound of one, Eq. (48b) can be replaced by

Level IIIb: $\frac{1}{k}\left(\frac{\partial k}{\partial T}\right)(T_0 - T_1) \ll 1$ (48c)

While the results given by Eqs. (48a,b,c) are something that "everyone knows," not everyone knows how to arrive at these constraints without solving the full boundary value problem and exploring special cases. In addition, the identification of various levels of simplification is an important concept to bring to the attention of students, for it allows us to move quickly to certain simple engineering solutions while reminding us of our obligation to be more thorough when time permits or necessity demands. Following up on our obligations is sometimes easy to do. For example, in the typical heat transfer course transient processes are always studied, and when exact solutions are available it is easy to remind students of prior constraints that were developed on the basis of order of magnitude analysis. In the study of transient heat conduction in a flat plate one finds that Eq. (48a) can be replaced with $\alpha t/L^2 \geq 1$, thus providing a clear indication that the original estimation was overly severe. To support the result given by Eq. (48c), a homework problem associated with Eqs. (22) through (25) does rather nicely. The process of following order of magnitude estimates with exact solutions is an attractive method of encouraging students to develop their own assumptions, restrictions and constraints. As they gain confidence in this process, chapter titles become guidelines for the voyage rather than constraints for the next exam.

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