Supplement to InTech Magazine
April 2003

Inside and out

By Francesco Pompei

Math model allows for greater production speed, cost savings.

Infrared temperature measurement methods of production processes are limited to material surfaces and thus have a serious limitation in thermal process monitoring, particularly when considering speed increases.

To overcome this limitation, a heat balance equation is derived in which the material surface temperature data is combined with other noncontact temperature data to calculate the internal temperature of the product, which in turn is used to optimize control to increase speeds. The derivation, via a mathematical model of unsteady heat transfer, is derived using an application of the LaPlace Transform method, which is shown to be an easy form for the design of measurement systems to estimate material internal temperature by noncontact means.

The model results are in agreement with experimental data in tire manufacturing, where hundreds of actual installations of such noncontact systems are successfully increasing tire production speeds by optimizing the vulcanizing time to the initial conditions of the green tire. The method extends to any thermal process such as food processing, printing, and laminating.

Tire success

A common problem in thermal processing in production is lack of control of the initial condition of the materials to be processed. They may be stored in a cold or hot warehouse, depending on the climate and season. Or the material may have just come in by truck, and there is no certainty as to bulk temperature. Or the materials may have come from another process in the same plant but with a completely unknown time at room ambient.

If you know the initial bulk temperature, you can reduce the total time in an oven by increasing conveying speed and adjusting oven temperature distribution. Without this temperature information, the oven time must be sufficiently long to accommodate the worst-case initial condition. For nonmetals, surface temperature alone, which you can obtain with infrared sensing devices, is insufficient, due to the large gradient from the material surface to the interior. Accordingly, a more sophisticated technique is required based on easily measured variables yet is robust enough to work under real world factory conditions.

A specific application actually researched and installed was for tire vulcanizing for a major tire manufacturer. The process consists of "cooking" tires under heat and pressure in special molds one at a time in individual presses. By measuring the "green" tire temperature immediately prior to vulcanizing, press time could be adjusted to maximize throughput and thus increase plant capacity with almost no capital investment—a significant accomplishment compared with adding capacity to a $100 million plant conventionally.

Initial experimental work immediately indicated that employing surface temperature alone would result in unacceptable errors. A new method could solve a simple steady-state heat balance equation at the tire surface and thus provide the internal temperature with a simple noncontact device.

The new method called for constructing infrared (IR) thermocouples with a heat balance circuit, calibrating them to the correct "K" value, and then installing them in the tire plant with very good tracking of actual internal temperatures. Hundreds of tire presses were placed under the control of this method, and they have produced with excellent results, increasing throughput about 10%. This is especially effective in the summer, when green tires warm up just by storage in hot warehouses prior to vulcanizing.

New frontiers

Despite the success, the underlying analysis was largely empirical, with no theoretical support for the simple steady-state model. Thus there was considerable uncertainty as to whether the method may apply to other processes or even to other tire plants. Because of that uncertainty, a more complete analytical model was required to provide the design parameters necessary for a successful application and to minimize the time and cost of empirical investigations in actual plants.

The more analytical model comes by constructing the unsteady differential equations governing heat conduction. The form of the solution includes all the attributes needed to apply to the problem of determining internal temperature by noncontact measurement and a simple calculation:

1) The coefficient K_1 necessary to program the IR device is clearly identified.
2) The coefficient K_2, which represents an uncontrolled initial condition error, is clearly identified.
3) The coefficients now emerge with conventional dimensionless heat transfer groups: *the Fourier No.* (*Fo*) characteristic heat conduction time and *Biot No.* (*Bi*) ratio of surface transfer rate to conduction.

The variation of K_2 , K_1 with *Fo* at the *Bi* is calculated for the thermally processing tires and, for comparison, for food. Note that the experimental value $K = 0.31$ is directly predicted.

Extending the model to the case of employing the IR sensors for speed increase, we employ the result

$$T_c = K_1(T_s - T_\infty) + T_s + K_2(T_s - T_o)$$

Because we wish to keep the surface temperature and internal temperature the same (or with a fixed relation), set $T_c = T_s$, which results in

$$\frac{(T_\infty - T_s)}{T_s - T_o} = \frac{K_2}{K_1} = (\Delta T)$$

Because K_2/K_1 is a function only of material properties and characteristic time τ, where τ at constant material properties depends only on process speed, a new ratio can be formed as

$$\frac{V_{new}}{V_{old}} = \frac{(\Delta T)_{new}}{(\Delta T)_{old}}$$

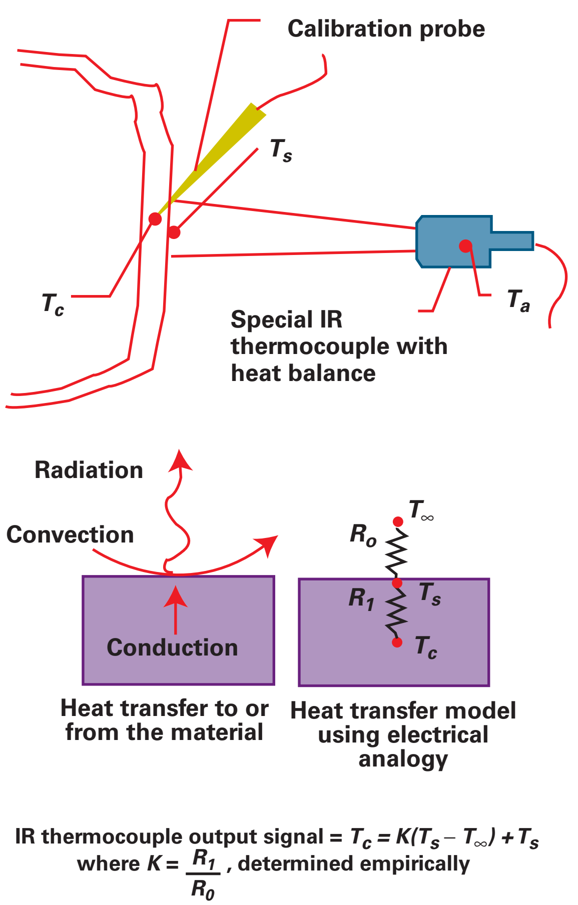
where

$$\Delta T = \frac{T_\infty - T_s}{T_s - T_o}$$

This expression, called the *Speed Boost Equation* (SBE), can then be a control algorithm to maintain correctly balanced thermal input to produce consistent product temperature profiles from the surface to the center, at various speeds V. For large speed changes—>10%, for example—material and heat transfer characteristics may become nonlinear and thus require renormalization of the value of K_2/K_1 at more than one point until the final desired speed is reached.

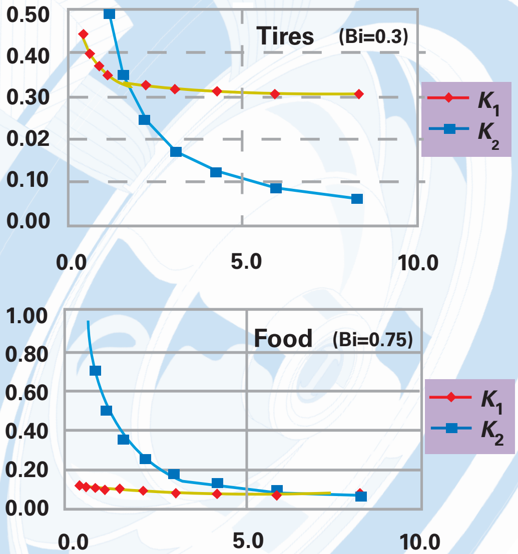
The physical interpretation of the SBE is that the ratio of energy supplied by the heat source at T_∞ to the product with surface temperature T_s, divided by the energy level difference between the initial state T_o and final state T_s, must hold constant at a constant speed. Accordingly, if the product temperature T_s is to be constant, and the speed is constant, the initial and source temperatures must remain controlled to maintain the balance in the SBE.

Tire probe

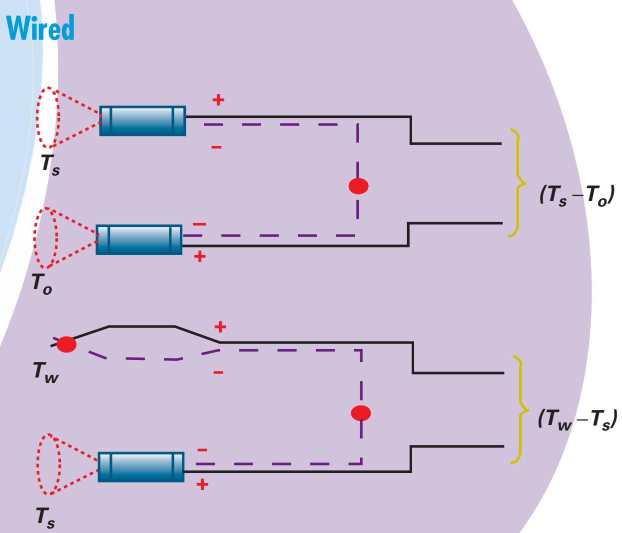


Probing tires thermocouple probe developed with built-in capability to solve the steady-state heat conduction duration for the tire. Calibration probe goes in initial setup to determine the value of the coefficient *K*.

Industry applications



For tires, K_1 (= K) asymptotes to the experimental value 0.31 at *Fo*~2. For food, K_1 is nearly independent of *Fo*.



Infrared thermocouples wired differentially (top) and with contact t/c to provide highly accurate ΔT.

For speed increase consideration as in the case of tires, with vulcanizing estimated at 200°C, if the initial temperature elevates by 20°C, you can immediately compute the speed increase as 10%, which agrees with the experimental result.

$$\frac{V_{new}}{V_{old}} = \left(\frac{T_\infty - T_s}{T_s - T_o}\right)_{new} \left(\frac{T_s - T_o}{T_\infty - T_s}\right)_{old} =$$

$$\frac{(T_s - T_o)_{old}}{(T_s - T_o)_{new}} \approx \frac{(200-0)}{(200-20)} \approx 1.1$$

Note the importance of the denominator, or preheat term, for speed increases. As in the case of tires, the source temperature for many thermal processes is limited by equipment or materials, while the product temperature is to be precisely held. The only variable available for speed increase is preheat (i.e., reducing the quantity $[T_s - T_o]$).

Industry applications

Applying the SBE to laminating processes, a 25% speed increase may occur by increasing the heating roll temperature from 105°C to 120°C, holding all else constant. The same increase could be achieved by providing preheat to 48°C without changing the source temperature.

In an example of a high-speed color copier, which has as the heat source the fuser roll temperature, the product temperature is the copy itself, and the initial temperature is at the feed paper. Inks for color copies are particularly temperature sensitive, due to the strong viscosity dependence on temperature. Accurate control is very important to maintain quality at maximum possible speed (a highly competitive selling point for manufacturers). Applying the SBE with the appropriate IR sensors allows maximal speeds under all conditions, especially if a preheat stage is fitted to the design.

In the graphics industry, you can show how to control the temporizing roll in waterless printing by using the SBE with the appropriate sensors. Manipulating the SBE and expressing the result as a control algorithm with conventional proportional-integral-derivative (PID) parameters gives the new equation

$$(T_w - T_s) = \frac{V}{K_2 / K_1}(T_s - T_o) + \text{PID}(T_s - T_{\text{set point}})$$

for controlling the cooling water temperature T_W. This form is expressed as controlling differences because an attribute of the preferred IR sensor types, infrared thermocouples, is that they can be wired differentially to produce an extremely accurate ΔT. For many applications, the required accuracy would limit the use of conventionally amplified IR devices, especially in the very sensitive denominator terms in the SBE, where small differences have a large effect.

Employing IR sensing to accurately control thermal processing—especially to increase process speeds—must include provisions for the difference between the surface temperature, which you can directly measure, and the bulk material temperature, which you must indirectly measure.

By employing a simple result of a complex mathematical model, you can estimate the bulk temperature from surface temperatures, ambient temperatures, material properties, and speed.

By extending the model, a result called the SBE can directly work with appropriate IR sensors to increase production speeds while maintaining material temperature characteristics. IT

Behind the byline

Dr. Francesco Pompei founded Exergen Corp., where he now serves as president, in 1980. He holds B.S. and M.S. degrees from the Massachusetts Institute of Technology and S.M. and Ph.D. degrees from Harvard University, where he has an appointment in the physics department.