Aspects of increased production speeds via IR control of product internal temperature

by F Pompei, Exergen Corporation

The model results are in agreement with experimental data in tyre manufacturing, where hundreds of actual installations of such non-contact systems are successfully increasing tyre production speeds by optimising the vulcanising time to the initial conditions of the green tyre. The method is extended to any thermal process and examples for food processing, printing and laminating are given.

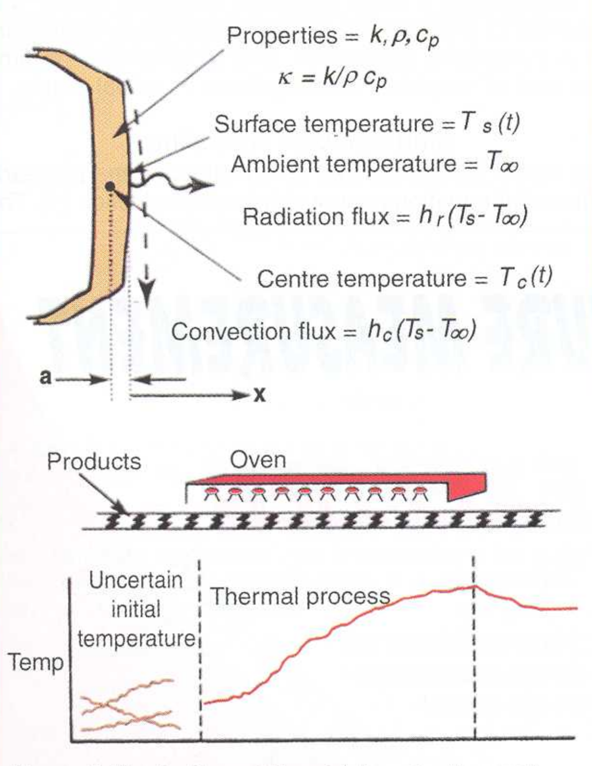


Figure 1: Illustration of time history for thermal processing products moving through an oven

Résumé

Francesco Pompei is president and founder of Exergen Corporation, developer and manufacturer of IR temperature sensors. He holds under-graduate and graduate degrees from MIT, and continues as an active scientist in human thermo-regulation physics in a special PhD program at Harvard.

Francesco has more than 20 patents in thermo-regulation technology for use in industrial instrumentation and medical applications.

Exergen is locally represented by Absolute Automation.

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 non-contact temperature data to calculate the internal temperature of the product, which in turn is used to optimise control to increase speeds.

Empirical success with tyres

A common problem in thermal processing during production is the lack of control of the initial condition of the materials to be processed. For example, the storage of materials could be in a cold or hot warehouse, the temperature may vary depending on the climate and season; it could have just been delivered by truck and there is no certainty as to bulk temperature; or the materials may have come from another process in the same plant, where the time it has been at room ambient is unknown.

Referring to *Figure 1* it can be seen that if the initial bulk temperature were known, the total time in an oven could be reduced 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 non-metals, the surface temperature alone, which can be obtained with infrared sensing devices, is not sufficient due to the large gradient from the material surface to the interior. Accordingly, a more sophisticated technique is required which is based on easily measured variables, yet is robust enough to be used in real-world factory conditions.

A specific application for tyre vulcanising was actually researched and installed at a major tyre manufacturer. The process for tyre vulcanising is similar to the process illustrated in *Figure 1*, except that it is not continuous. Tyres are 'cooked' under heat and pressure in special moulds, one at a time, in individual presses. By measuring the 'green' tyre temperature immediately prior to vulcanising, press time could be adjusted to maximise throughput. This in turn increases plant capacity with almost no capital investment - a significant

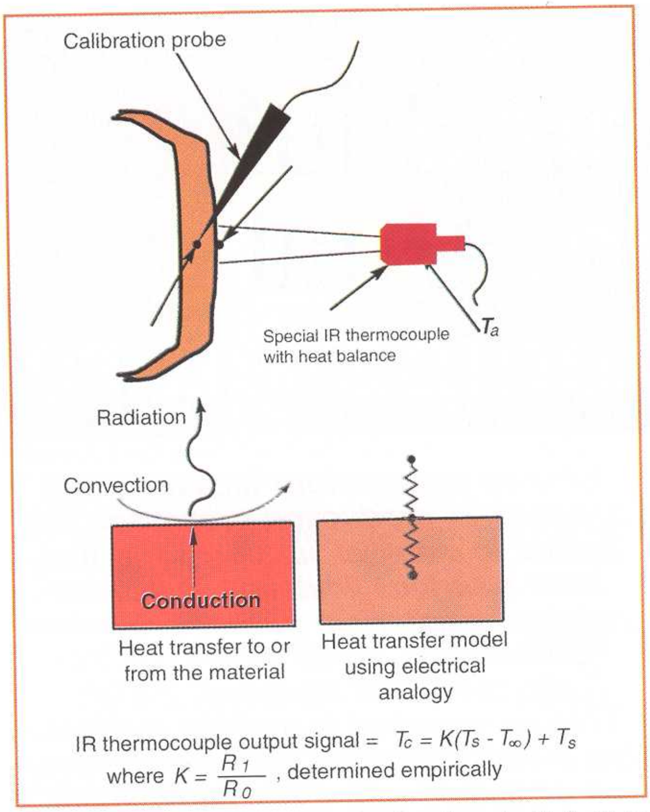


Figure 2: IR thermocouple probe developed with built-in capability to solve the steady-state heat conduction equation for the tyre. Calibration probe is used in initial setup to determine the value of the coefficient K

accomplishment compared to adding capacity to a $100 M plant conventionally.

Initial experimental work immediately indicated that employing surface temperature alone would result in unacceptable errors. Accordingly a method was proposed that solved a simple steady-state heat balance equation at the tyre surface, and thus could provide the internal temperature with a simple non-contact device. This method is described in *Figure 2*.

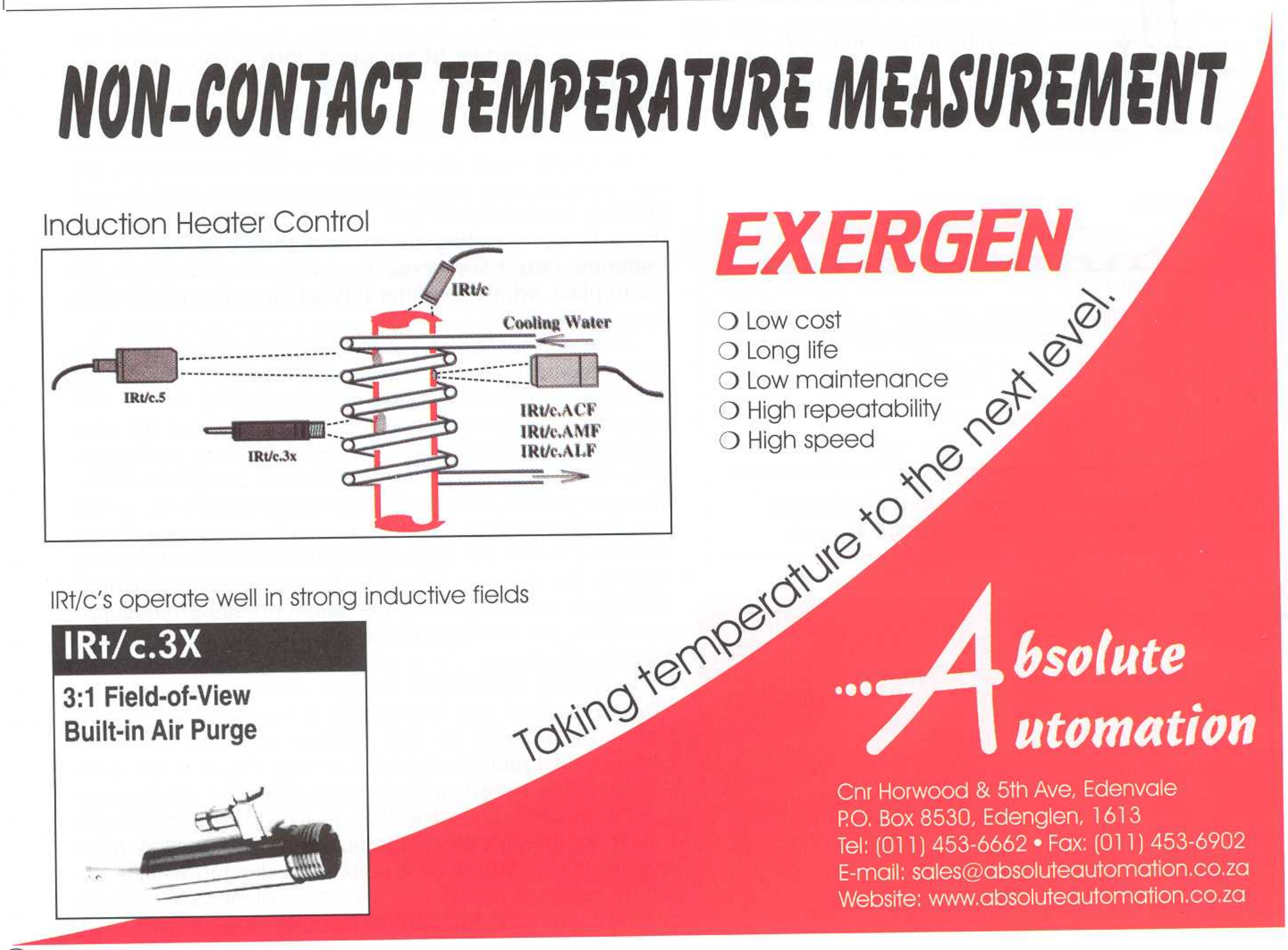
IR thermocouples with a heat balance circuit were constructed and calibrated to the correct 'K' value as per *Figure 2*. These were installed in the tyre plant (see *Figure 3*) with very good tracking of actual internal temperatures. Hundreds of tyre presses were placed under the control of this method, and for seven years they have produced with excellent results, increasing throughput by about 10%. This is especially effective in the summer when green tyres are warmed by storage in hot warehouses prior to vulcanising.

Despite the success, the underlying analysis was largely empirical, with no theoretical support for the simple steady-state model, and thus there was considerable uncertainty as to whether the method may be applied to other processes, or even to other tyre manufacturing plants.

Accordingly, a more complete analytical model was required to provide the design parameters necessary for a successful application, and to minimise the time and cost of empirical investigations in actual plants.

Mathematical modeling

The model can be derived by constructing the unsteady differential equations governing heat conduction [1]. The



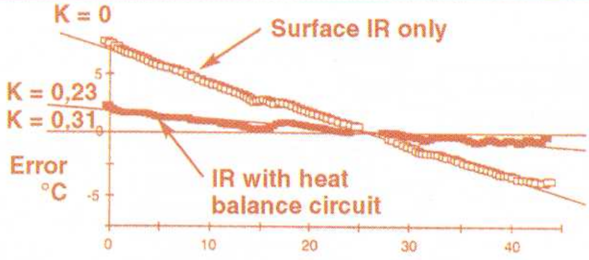


Figure 3 (a): Data for tyres removed from freezer and placed in room ambient

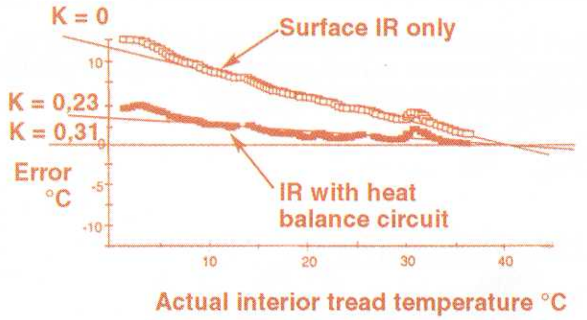


Figure 3 (b): Data for tyres removed from freezer and placed in oven

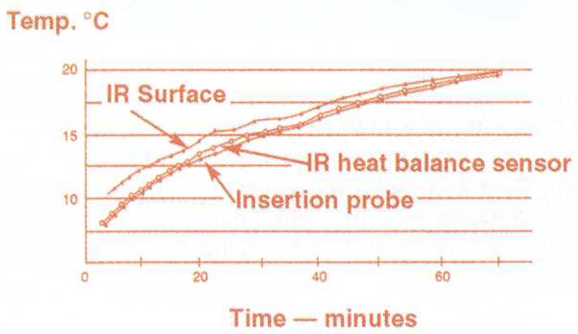


Figure 3 (c): Temperature vs time for tyres removed from freezer into room temperature

Figure 3: Measured error between heat balance IR thermocouple and actual tyre temperatures for initial estimate of K = 0,23. Final value of K = 0,31 which reduces errors to near zero.

form of the solution includes all of the attributes needed to apply the problem of determining internal temperature by non-contact measurement and a simple calculation:

- the coefficient K_1 necessary to program the IR device is clearly identified (= K of *Figure 2*)
- the coefficient K_2, which represents an uncontrolled initial condition error, is clearly identified
- the coefficients 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

Figure 4 shows the variation of K_2, K_1 with Fo at the Bi calculated for the thermally processed tyres, and for comparison to food. Note that the experimental value K - 0,31 is directly predicted.

Results of this analysis can be used to develop the speed boost equation (SBE) which can then be used as 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, for example >10%,

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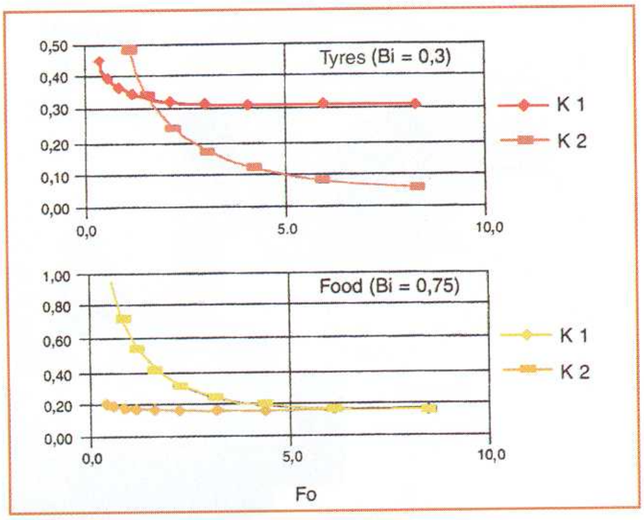


Figure 4: For tyres K_1 (= K) asymptotes to the experimental value 0,31 at Fo SYMBOL 2. For food K_1 is nearly independent of Fo

material and heat transfer characteristics may become non-linear, and thus require re-normalisation of the value of K_2/K_1 at more than one point until the final desired speed is reached.

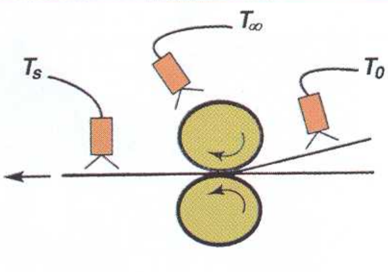
The physical interpretation of the SBE is that the ratio of energy supplied by the heat source at T_∞ to the product with surface temperature T_s, divided by the energy level difference between the initial state T_0 and final state T_s must be held constant at a constant speed. Accordingly, if the product temperature T_s is to be held constant, and the speed is held constant, the initial and source temperatures must be controlled to maintain the balance in the SBE.

Applying the SBE to laminating processes, as illustrated in *Figure 5*, a 25% speed increase may be realised by increasing the heating roll temperature from 105 to 120°C, holding all else constant. The same increase could be achieved by providing preheat to 48°C without changing the source temperature.

Laminating
Existing setup:
T∞ = 105°C
Ts = 85°C
To = 25°C

New setup:
T∞ = 120°C
Ts = 85°C
To = 25°C

Potential speed increase: 25%



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

Figure 5: Speed boost for laminating process

Figure 6 shows an example of a high speed colour 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 colour copies are particularly temperature sensitive due to the strong viscosity dependence on temperature. Here accurate control is very important in order to maintain quality at maximum possible speed (a highly competitive selling point for manufacturers). Applying the SBE with appropriate IR sensors allows maximal speeds under all conditions, especially if a preheat stage is fitted to the design.

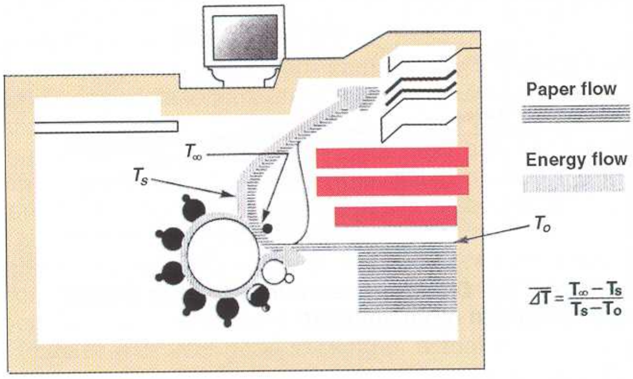


Figure 6: Speed boost applied to high speed copier by placing IR sensors at feed paper, fuser roll, and printed copy as it discharges from fuser roll

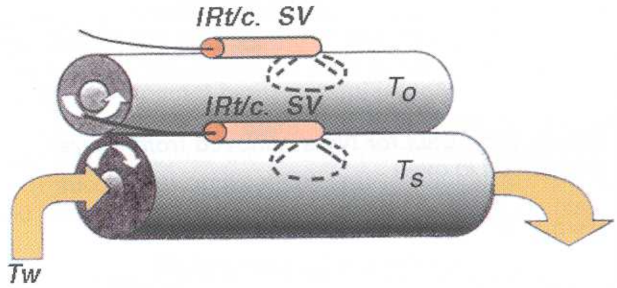


Figure 7: High performance cooling system with both T_s and T_o monitored with IR t/c sensors

Figure 7 is another example from the graphics industry, showing how the temporising roll in waterless printing may be controlled by using the SBE with the appropriate sensors.

Conclusion

Employing IR sensing to accurately control thermal processing, especially to increase process speeds, must include provisions for the difference between the surface temperature, which can be directly measured, and the bulk material temperature, which must be indirectly measured. By employing a simple result of a complex mathematical model, the bulk temperature can be estimated from surface temperatures, ambient temperature, material properties and speed. By extending the model, a result we call the SBE can be directly employed with appropriate IR sensors to increase production speeds while maintaining material temperature characteristics.

References

[1] Pompei F. "Increasing production speeds via IR control of product internal temperature" Measurements+Control, October 2000.

Take Note

- math modeling of the process allows optimisation
- full mathematical development of the model, along with more detailed examples is available from the author by email (fpompei@exergen.com)

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Aspects of increased production speeds via IR control of product internal temperature

published in

ELECTRICITY + CONTROL

in the May *issue of the year* 2002

Editor

Publisher

Crown Publications c.c.