10 The Energy Aspects of Mixing Rubber

10.1 Introduction

The energy aspects of rubber mixing have been a focal point of some research activity. Particular attention has been given to the process involving internal mixers. A state-of-art review was published on this subject [1]. A method was proposed for control and scale-up which was based on the energy input for mixing [2]. Those properties affected by the degree of mixing were evaluated as functions of mixing energy [2, 3, 4]. This method was used for evaluating the performance of different types of elastomers and carbon blacks in internal mixers [5, 6]. Although the method treats the internal mixers essentially as a ‘black box’, it represents significant progress in understanding the mixing process. It permits comparison of the efficiency of different types of equipment and the evaluation of the ease of mixing of a given formulation.

The energy aspect is not only of technological importance but also an economic concern. It leads to two questions: how the input energy is spent and how much is actually necessary. The answer to the first question is to take an energy balance, which is a method of ‘book keeping’ on the income and expenditure in terms of energy. The second question requires elucidation of mixing mechanisms and calculation of theoretical energy requirements. The mill-mixing involves human participation. Therefore, the energy spent in the machine operation is only a part of the overall energy aspect. It is not easy to quantify the energy balance. On the other hand mixing with an internal mixer is amenable to taking energy balance. The foregoing discussion is about the operation of internal mixer only and an example is a Banbury type mixer.

The examination of mixing mechanisms will also deal primarily with the internal mixer, because the energy requirements must be determined quantitatively. A discussion of this subject will be given in Chapter 11.

10.2 Energy balance

Because mixing involves viscous heat generation and simultaneous cooling, heat transfer measurement is a necessary part of calculating the energy balance.
Precise data gathering requires extensive instrumentation, which becomes prohibitively expensive. However, with reasonable assumptions and approximations, an overall energy balance of the mixing operation may be obtained using relatively simple instrumentation. This work is an example of such a study of the operation of a laboratory Banbury mixer with a powdered rubber compound.

10.2.1 Experiment

The aim of the experimental work is:

(1) to define the operating conditions of the machine as closely as possible,
(2) to establish a reproducible operation,
(3) to collect as much data as possible within a rather short time operation, i.e., about 1.5 minutes.

The characterisation of the mixing results is outside the scope of this work. The emphasis is on the analysis and not on the optimisation of the process.

Sample

A preblended powdered rubber compound was charged into the mixer, instead of separately charging a slab of rubber and carbon black. This was done to minimise the variability in the charging procedure and to avoid gross inhomogeneity at the beginning of the mixing.

The formulation is given in Table 10.1. The raw elastomer was an NBR copolymer powdered rubber with a Mooney index of 80 (ASTM D1646 [7]). The powder was preblended with a high-intensity Henschel mixer.

<table>
<thead>
<tr>
<th>Table 10.1 Compound Formulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
</tr>
<tr>
<td>Rubber</td>
</tr>
<tr>
<td>ZnO</td>
</tr>
<tr>
<td>Stearic acid</td>
</tr>
<tr>
<td>N550 carbon black</td>
</tr>
<tr>
<td>DOP</td>
</tr>
<tr>
<td>TMTD</td>
</tr>
<tr>
<td>4,4′-Dithiodimorpholine</td>
</tr>
</tbody>
</table>

DOP: dioctyl phthalate
TMTD: tetramethyl thiuram disulphide
• **Equipment and operating conditions**

The internal mixer and measuring instruments were as follows:

1. A Banbury mixer (size BR) with the narrowest gap between the blade and the wall of 2.39 mm and a sectional chamber diameter of 101.6 mm.

2. A built-in thermocouple for stock temperature measurement which was in a thermocouple well located above the rotors in the middle of the chamber and extending about 25 mm in a 45 degree downward direction from the right-hand wall.

3. A recording watt-meter and a power integrator.

4. A portable pyrometer for direct measurement of the stock temperature and temperatures of various parts of the machine.

5. Thermometers for the measurement of the cooling-water temperature.

6. A flow meter for the cooling water.

All thermometers had been precalibrated. The operating conditions of the mixer are given in Table 10.2.

<table>
<thead>
<tr>
<th>Table 10.2 Operating Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample charge</td>
</tr>
<tr>
<td>Revolution rate</td>
</tr>
<tr>
<td>Ram pressure</td>
</tr>
<tr>
<td>Cooling water flow rate</td>
</tr>
</tbody>
</table>

**10.2.2 Experimental programme**

The programme consisted of three sets of experiments. The first set, Experiment I, was performed in 1972; the second, Experiment II and the third, Experiment III, were performed in 1981. A different operator performed the mixing for each set of experiments.

In Experiment I, the machine had been prewarmed by circulating cooling water which had been adjusted to 35-40 °C. The circulation of water had been started well ahead of
the mixing runs so that the machine, a metal block of large mass, was preheated to an approximate equilibrium temperature. Five runs were made to assure energy data reproducibility. The sixth run was terminated at an intermediate stage of mixing for the direct measurement of the stock temperature at this stage.

The thermometer for the outlet water did not register a significant temperature rise. The subsequent calculation of the heat transfer indicated that the expected temperature rise was so small that a more precise thermometer was required.

In Experiment II, the cooling water was at room temperature in the beginning. The machine was prewarmed by the first three mixing runs; the energy data of these runs were not used for the present calculation. Subsequently, another three runs were made for obtaining the energy balance. In order to measure the total heat removed by the cooling water, a given amount of water in a reservoir of 84 litres was recirculated and the temperature difference between the beginning and the end of the mixing was measured with a thermometer accurate to 0.05 °C.

Experiment III was essentially the same as Experiment II, except that the curatives were omitted from the formulation. This was done to ensure that a premature cure, which might contribute to errors in the energy balance, did not take place. The first two somewhat longer runs were used for prewarming the machine. The subsequent four runs were made for obtaining the energy balance. Each run was terminated at a different stage of mixing in order to measure the stock temperature directly.

The mixing performance, as observed by the power input and the stock temperature, was quite reproducible for all mixing runs in the three sets of the experiment. This confirmed that a premature cure reaction did not take place.

**Measurement of machine temperature**

The machine temperature was measured immediately before and after the runs with a portable pyrometer. The measurements were always made at the same place on the machine. The outside wall had a square bulge, which was a convenient spot to use. It was approximately 50 mm from the right-hand wall of the chamber. The rotor temperature was measured in the centre of the broad side of the blade at the largest gap from the wall. This part is thought to represent the average temperature. At the edge of the blade, the temperature may be higher because of the high shear rate at the narrowest gap. The chamber-wall temperature was measured near the top of the door. The order of temperature measurements was first the rotor, followed by the chamber-wall, and then the outside wall. After each run, the stock temperature was taken first, and then the machine temperatures were measured. The measurements were made rapidly, and the highest temperature was measured first in order to minimise the error due to cooling.
• **Measurement of stock temperature**

The final stock temperature was measured immediately after the door was opened at the corresponding spot where the rotor temperature was measured. However, because the stock was still banded on the rotor, it was not possible to see whether or not the spot was exactly at the centre of the broad side of the blade.

### 10.2.3 Results

• **Temperature measurements**

The temperature data of some of the mixing runs are given in Table 10.3; the data of the runs not shown here were very similar to the ones in the table. Within a given set of experiments, the cooling-water temperature gradually increased a few degrees. However, during each mixing run, the cooling-water temperature remained approximately constant.

<table>
<thead>
<tr>
<th>Table 10.3 Temperature Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiment No.</strong></td>
</tr>
<tr>
<td>Run No.</td>
</tr>
<tr>
<td>Run time, s</td>
</tr>
<tr>
<td><strong>Cooling water, °C</strong></td>
</tr>
<tr>
<td>Inlet (start/finish)</td>
</tr>
<tr>
<td>Reservoir (start/finish)</td>
</tr>
<tr>
<td><strong>Machine temperature, °C</strong></td>
</tr>
<tr>
<td>Rotor (start/finish)</td>
</tr>
<tr>
<td>Chamber wall (start/finish)</td>
</tr>
<tr>
<td>Outside wall (start/finish)</td>
</tr>
<tr>
<td><strong>Stock temperature at finish, °C</strong></td>
</tr>
<tr>
<td>Direct measurement, $t_1$</td>
</tr>
<tr>
<td>Thermocouple, $t_2$</td>
</tr>
<tr>
<td>$t_1-t_2$</td>
</tr>
</tbody>
</table>

The temperatures of the rotor and chamber-wall were not exactly reproducible, partly because of the non-uniform temperature within the compound. Moreover, the measurement of the steel surface with a temperature probe involves a somewhat larger
error. However, the average temperature rise of these parts can easily be estimated. The temperature of the outside wall of the machine increased by 1-3 °C during a run. This must have resulted from the temperature rise of the compound rather than from the cooling water, which was in many cases warmer than the outside wall.

Direct measurements of the stock temperature indicated that there was a large run-to-run variation. This was interpreted to represent temperature non-uniformity within one batch, which was as much as ±13.5 °C. Also, the direct measurements indicated a 12-39 °C higher temperature than that indicated by the built-in thermocouple. The latter, being placed in a rather large well, might have been cooled by the large heat sink of the machine body.

Examples of the continuous recording of the stock temperature are shown in Figure 10.1. The recorded starting temperature is that of the machine rather than the stock temperature, which was 24 °C. In all three sets of experiments, the temperature readings increased as the mixing runs were repeated. However, there is a reproducible pattern in all the temperature recordings, namely, the initial rapid increase tapers off at about 25-30 seconds and then, another rapid increase occurs until 40-50 seconds. Thereafter, the temperature increase is much more gradual.

![Figure 10.1 Temperature curves recorded by the thermocouple for Experiment III, Runs 3 and 6 (see Table 10.3 for experimental details).](image)

Reprinted with permission from N. Nakajima, E. R. Harrell and D. A. Seil, Rubber Chemistry and Technology, 1982, 55, 2, 456. Copyright 1982, Rubber Division of the ACS.
A method for estimating the true compound temperature is illustrated in Figure 10.2, which shows the temperature recorded by thermocouple, $t_2$, the stock temperature, $t_1$, measured directly by a probe and the stock temperatures estimated from the temperature difference, $t_1 - t_2$, of other runs. These $t_1 - t_2$ values were added to the $t_2$-curve of this run to obtain the $t_1$-curve. It was assumed that the temperature difference between the $t_1$-curve and the $t_2$-curve increased smoothly with the rise of the stock temperature. This is based on the previously stated interpretation that the temperature difference, $t_1 - t_2$, is caused by the heat-sink effect on the thermocouple. Such an effect is expected to increase with rising stock temperature. The fact that the pattern of $t_2$-curves is very reproducible means that the temperature non-uniformity within the compound is not registered by the thermocouple. This is probably due to the time lag of the thermocouple, which averages out the temperature non-uniformity of the very rapidly sweeping compound.

Figure 10.2 Method of estimating correct temperature of the compound for Experiment II, Run 4 (see Table 10.3 for experimental details). Solid curve, temperature recorded by thermocouple, $t_2$; broken curve, estimated stock temperature, $t_1$; ○ stock temperature measured by probe, $t_i$; △ stock temperature estimated from the temperature difference, $t_1 - t_2$, of other runs.

Reprinted with permission from N. Nakajima, E. R. Harrell and D. A. Seil, Rubber Chemistry and Technology, 1982, 55, 2, 456. Copyright 1982, Rubber Division of the ACS.
Science and Practice of Rubber Mixing

• **Mechanical energy input**

Figure 10.3 shows a recorder trace of the power input; the input of mechanical energy is the area under the curve. Also, shown is the stock temperature, estimated according to the method described previously. Initially, the power level is high and approximately constant. This part corresponds to the rapid increase of the stock temperature. The carbon black incorporation is almost completed before the dusting period. The dusting period occurs when the ram is lifted up and the material remaining in the charge hole is swept down into the chamber. That is why the power input during the dusting period is lower. After the ram is down, the power goes up again but then gradually decreases. This part corresponds to the more gradual increase of the stock temperature.

Figure 10.3 Power input (---) and temperature curves (------) for Experiment I, Run 4 (see Table 10.3 for experimental details).

Reprinted with permission from N. Nakajima, E. R. Harrell and D. A. Seil, Rubber Chemistry and Technology, 1982, 55, 2, 456. Copyright 1982, Rubber Division of the ACS.

• **Method for evaluating energies**

**Mechanical energy input.** The mechanical energy input was calculated in the following sequence. First, the area under the kW-time recorder trace was integrated. This gives the energy input as a function of time. The total energy input was checked against the reading of the power integrator. This energy, however, does not represent the real work done on
the material because one part of the energy represents the electrical loss in the motor and another the mechanical loss in the machine.

The efficiency cannot be obtained from the differences of the energy inputs between loaded and unloaded operations, because the losses depend upon the load. In the present operations, the energy required to run the unloaded machine for the corresponding period of time was only 6-6.5% of the total energy input for mixing. However, for a large mixing machine, the real loss is usually 10-15% [1]. On the other hand, an example involving the extrusion of thermoplastic materials gave an efficiency of 75%. Since a small mixer was used in this experiment, the efficiency may be somewhat lower than that of the large mixers. From the energy calculation at the end of the mixing cycle, the efficiency was estimated to be 79%, as will be shown later. Then the 79% efficiency was assumed to be independent of the progress of mixing. This approximation is justified, because the power input does not change enough to affect the efficiency.

- **Enthalpy increase of the compound**

As the mixing progresses, the temperature of the stock rises. The accompanying increase of enthalpy, ΔH, was calculated according to

\[ \Delta H = \sum m_i C_{pi} (t - t_0) \]  

(10.1)

where \( m_i \) is the mass,
\( C_{pi} \) is the specific heat of the components,
\( t \) is the stock temperature;
\( t_0 \) is the room temperature, 20 °C for Experiment I and 24 °C for Experiments II and III.

The mass–average value of \( C_p \) of the compound, 1.5 J/g-K, was used for the actual calculation. This value was estimated, assuming that the \( C_p \) of SBR rubber, 1.9 J/g-K [8], represented the \( C_p \) of rubber and ingredients other than carbon black, while \( C_p \) of carbon was taken to be 0.76 J/g-K [9].

- **Heat loss from the machine surface to the room.**

The following formulae [10] were used to estimate the heat loss from the machine surface.

For convection,

\[ q_c = hA \Delta t_s \]  

(10.2)
where $q_c$ is the rate of heat loss to the room by convection in watts, $h$ is a convection coefficient in $W/(m^2\cdot K)$, $A$ is an effective surface area of the machine in $m^2$, $\Delta t_s$ is the temperature difference between the machine surface and the room in K.

The convection coefficient for heat loss from surfaces by convection to air at atmospheric pressure and ordinary temperatures is given by the equation for vertical plates as

$$h = 0.28(\Delta t_s / L)^{1/4}$$

where $L$ is the characteristic dimension of machine in metres.

For radiation,

$$q_R = A\varepsilon\sigma(T^4 - T_0^4)$$

where $q_R$ is the rate of heat loss by radiation in watts, $\sigma$ is the Stefan–Boltzmann constant for a black body in $W/(m^2\cdot K^4)$, $\varepsilon$ is emissivity, a coefficient for a particular surface, $T$ is the absolute temperature of the surface in K, and $T_0$ is the room temperature in K. The numerical values of the constants are given in Table 10.4.

<table>
<thead>
<tr>
<th>Table 10.4 Quantities for Heat Transfer Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Convection</strong></td>
</tr>
<tr>
<td>$A=0.24 \text{ m}^2 \ a$</td>
</tr>
<tr>
<td>$L=0.25 \text{ m} \ b$</td>
</tr>
</tbody>
</table>

$a$ : Approximate surface area of the mixing chamber  
$b$ : Approximate dimension of the vertical surface  
$c$ : [11]  
$d$ : Painted surface or oxidised steel surface [12]

The overall rate of heat loss from the machine surface is

$$q_L = q_c + q_R$$

(10.5)
Because the temperature difference between the room and the machine surface remains approximately constant throughout the run, the total heat loss is

\[ Q_L = q_L \theta \]  \hspace{1cm} (10.6)

where \( \theta \) is the time in seconds.

- **Machine body as a heat sink**

If the machine is cold at the start of the mixing operation, a large amount of heat is used to raise the machine temperature, which eventually reaches approximately a steady state after several mixing cycles. In the present case, the machine body was pre-equilibrated either by circulating warm water or by performing a few mixing runs. In this way, the bulk of the heat sink effect was eliminated. The observations in Table 10.3 show that the outside-wall temperature of the machine remained approximately constant during a mixing cycle. However, the temperature of the outside wall went up 1-3 °C during the mixing cycle. This means that the heat-sink effect still existed. It is difficult to calculate the heat loss from this temperature-rise, because the exact portions of the machine which are involved cannot be estimated. Instead, the heat flow from the compound to the environment was evaluated in the following manner. One part of the heat flow was to the metal block between the mixing chamber and the cooling water. This part of the heat flow, \( Q_m \), raised the temperature of the metal block and was partially removed by the cooling water, \( Q_w \). Another part of the heat flow, \( Q'_m \), occurred through non-jacketed regions of the machine, e.g., the charge hole, the ram, and the rotor shafts. The sum of \( Q_m + Q'_m = Q_M \) constitutes the total magnitude of the heat-sink effect.

The magnitude of \( Q_m \) was calculated from

\[ Q_m = C_p m \Delta t_{av} \]  \hspace{1cm} (10.7)

where \( C_p = 0.46 \text{ J/g} \cdot \text{K} \) for steel, and the mass of the block and the rotor, \( m \), is estimated to be 21 kg, where jacketed. The average increase of the temperature was calculated from:

\[ \Delta t_{av} = (\Delta t_m + \Delta t'_m) / 2 \]  \hspace{1cm} (10.8)

where \( \Delta t_m \) is the observed temperature rise at the chamber wall (and the rotor surface) and \( \Delta t'_m \) is the temperature rise at the jacket surface. The latter was estimated from the known value of the heat transfer coefficient between steel surface and cooling water, \( U_w \), and from the rate of heat transfer to the cooling water, \( dQ_w / d\theta \). The averaging in equation (10.8) assumes a constant temperature gradient across the chamber wall, i.e., a steady state. This somewhat overestimates the actual heat loss because the heat flow is
not at a steady state [1]. Moreover, linear increases of $\Delta t$ and $\Delta t'$ with time were assumed, and this also somewhat overestimates the heat loss. However, these approximations do not seriously affect the present calculation.

For the calculation of heat flow through the unjacketed part of the machine, a semi-infinite solid wall with a uniform, unidirectional temperature gradient was assumed. On the assumption of a temperature rising linearly with time at the chamber wall and at the rotor surface, $\Delta t_{x0} = C\theta$, the equation for the heat flow becomes [13]:

$$\Delta t_x = C\theta \left(1 + \frac{x^2}{2\alpha\theta}\right) \text{erfc} \left(\frac{x}{2\sqrt{\alpha\theta}}\right) - \frac{x}{\sqrt{\pi\alpha\theta}} \exp\left(-\frac{x^2}{4\alpha\theta}\right)$$

(10.9)

where $\Delta t_x$ is the temperature difference between the location $x$ and infinite distance at a fixed time $\theta$. The other parameters are $C$, the coefficient of the linear temperature rise and $\alpha$, the thermal diffusivity of steel, given by

$$\alpha = \frac{k}{\rho C_p}$$

(10.10)

where the thermal conductivity, $k$, of steel is 45 W/m$ \cdot$ K,

the density, $\rho$, is $7.8 \times 10^6$ g/m$^3$,

and the specific heat, $C_p$, is 0.46 J / (g $\cdot$ K). These values give a thermal diffusivity of

$$\alpha = 12.5 \times 10^{-6} \text{ m}^2/\text{s}$$

The values of $\Delta t$ were calculated as functions of $x$ at fixed values of $\theta$. This permitted evaluation of the temperature gradient, $(\partial t / \partial x)_{\theta,x}$ at $x = 0$. The corresponding heat flux is,

$$f = -k(\partial t / \partial x)$$

(10.11)

The total heat flow by conduction is,

$$Q_m' = A|\theta| d\theta = -kA|\theta|(\partial t / \partial x) d\theta$$

(10.12)

where the estimated surface area, $A$, is 0.04 m$^2$.

- Heat removed by cooling water

The heat removed by cooling water was calculated in two ways. The first used the observed temperature rise, $\Delta t_R$, of the cooling water in the reservoir:

$$Q_w = mC_p\Delta t_R$$

(10.13)
The second method evaluated $Q_w$ from the difference according to

$$Q_w = Q_t - (\Delta H + Q_M + Q_L)$$  \hspace{1cm} (10.14)

The first method was used only with the data at the end of the run. As stated before, the energy balance at this stage gave an average 79% efficiency for the machine. The second method was used to evaluate $Q_w$ as mixing progressed. The total energy input, $Q_t$, was calculated as previously explained, using 79% efficiency.

<table>
<thead>
<tr>
<th>Table 10.5 Energy Balance at End of Mixing Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment No.</td>
</tr>
<tr>
<td>Run No.</td>
</tr>
<tr>
<td>Input, kJ</td>
</tr>
<tr>
<td>(Power Integrator)</td>
</tr>
<tr>
<td>$\Delta H$, kJ</td>
</tr>
<tr>
<td>$Q_I$, kJ</td>
</tr>
<tr>
<td>$Q_M$, kJ</td>
</tr>
<tr>
<td>$Q_L$, kJ</td>
</tr>
<tr>
<td>Total Output, kJ</td>
</tr>
<tr>
<td>Efficiency, %</td>
</tr>
</tbody>
</table>

- **Energy Balance**

The energy balance data at the end of the mixing runs for Experiments II and III are summarised in Table 10.5. This calculation was not performed for Experiment I because direct measurements of $Q_w$ were not available. From these seven runs, the average efficiency of the machine was found to be 79%.

An example of the energy balance during the mixing is shown in Figure 10.4. For this example, the following values prevailed at the end of the mixing cycle:

$$\Delta H/Q_T = 41.3-46\%$$  

$$Q_I/Q_T = 0.2-0.6\%$$  

$$Q_M/Q_T = 12.3-14.6\%$$
$Q_W/Q_T = 39.6-45.1\%$

For the runs terminated after 30-55 seconds, the values were:

$\Delta H/Q_T = 54.5-55.4\%$

$Q_L/Q_T = 0.3-0.4\%$

$Q_M/Q_T = 10.0-12.7\%$

$Q_W/Q_T = 32.5-34.5\%$

Figure 10.4 Energy balance of internal mixer during mixing of powdered rubber compound. Curves: 1, $\Delta H$; 2, $Q_M + Q_L$; 3 $Q_W$. Results obtained from Experiment III, Run 4 (see Table 10.3 for experimental details).

*Heat Transfer*

*Calculation of heat transfer coefficient.* The heat removed by the cooling water, $Q_w$ is plotted with time, $\theta$ in Figure 10.5, for Experiment III, Run 4. The slope of this curve is the rate of heat transfer from the compound to water, $dQ_w / d\theta$. 

286
The overall heat transfer coefficient for heat transfer from the stock to cooling water is calculated from

\[ UA = \frac{dQ_w}{d(\theta(t - t_w))} \]  

(10.15)

where \( U \) is the overall heat transfer coefficient, \( W/(m^2\cdot K) \),

\( A \) is the area of heat transfer, \( m^2 \),

\( t \) is the average stock temperature,

and \( t_w \) is the cooling water temperature, \( ^oC \).

The values of \( U \) are plotted in Figure 10.6 for the period when the ram was down. The points indicated by the circles are the averages obtained from all the runs. Each data point fell within the range indicated by the error bars. In spite of the considerable scattering of the data, there are two observable trends: the heat transfer coefficient decreases as the mixing progresses and tends to level off; the scatter of the data diminishes as mixing advances. The scatter of the data may be related to inhomogeneity of the material and non-uniform temperature, both of which must decrease with the progress of mixing.
The data for the early stage for the mixing and the dusting period are not shown because they were not reproducible.

The high value of the heat transfer coefficient early in the process may be related to the carbon black that is exposed to the chamber wall. As the carbon black becomes completely incorporated, the heat transfer is between the rubber and the chamber wall. This explains the constant values eventually reached. From the heat transfer data, the incorporation of carbon black is seen to be almost complete after 40-45 seconds of mixing. This is the beginning of the dusting, which, experience had taught us, coincides with the completion of incorporation of carbon black.

10.2.4 Summary

An energy balance was obtained for the mixing of an elastomer compound in the internal mixer. The mixing operation was done reproducibly, and pertinent data were collected with relatively simple instrumentation. Out of the total mechanical energy input into the compound, 41-46% went to raise the temperature of the compound, and 40-45% was removed by the cooling water. The heat loss from the mixer wall to the room was very
small and negligible. This energy balance is based on the average temperature profile, which assumes uniform temperature of the stock.

The actual temperature measurement of the stocks gave temperature differences of as much as ±13.5 °C, indicating temperature non-uniformity within the stock. This is very plausible because rubber is a poor conductor, the shear field within the mixing chamber is exceedingly non-uniform, and thus, the viscous heating of the material is very non-uniform.

Heat transfer coefficients were evaluated for the overall heat transfer from the stock to the cooling water and for the heat transfer from the stock to the chamber wall. The data indicate that the compound was not uniform at the beginning of the mixing, in spite of the fact that a premixed powdered rubber was used. The non-uniformity must be in the degree of incorporation of carbon black rather than in the composition. There is also non-uniformity in the temperature. The heat transfer coefficient has a high value when the carbon black is on the surface of rubber but decreases to a constant value with the incorporation of carbon black into the rubber.

Although it is not the objective of this chapter to evaluate the effectiveness of mixing, the compound after curing gave mechanical properties which indicated thorough mixing.

References


Science and Practice of Rubber Mixing

7. ASTM D1646-99
   Standard Test Methods for Rubber-Viscosity, Stress Relaxation and Pre-Vulcanised Characteristics (Mooney Viscometer).


