The cohesive, or softening-melting zone plays a critical role in determining blast furnace performance and stability. The effect of changes in the permeability of softening-melting ore and the subsequent distribution of gases and liquids around the anisotropic packing structure of coke and ore layers in this region must be understood before the blast furnace can be adequately modelled. This study aimed to address issues related to cohesive zone formation through low-temperature experimentation. Two investigations of meltdown behaviour were performed, classified according to geometrical characteristics. The first ‘flat layer meltdown’ investigation examined the softening-melting of flat cohesive layers extending across the furnace diameter. This configuration matched that used in high-temperature softening-melting tests. The second ‘single layer meltdown’ investigation concentrated on a single cohesive layer embedded in a permeable packing. This configuration can be likened to a single cohesive layer in a permeable cohesive zone, where gas is able to bypass ore through intermediate coke slits as permeability is lost. The meltdown of flat cohesive zones was characterised by variability and gas channelling, promoting furnace instability and preventing accurate modelling. The meltdown of single layers demonstrated the possibility of structural variation between the surface and core, and the change in contribution of convection and conduction to heating.

KEY WORDS: blast furnace; cohesive zone; softening-melting; modelling.
formance. A continuous layer of wax (Series I) or solder (Series II) particles embedded between two layers of glass spheres in a cylindrical bed was chosen to represent the ore/coke-slit system.

2.2. Single Layer Meltdown

In the cohesive zone model of Gudenau et al., gas flow through a softening ore layer continues with increasing velocity as porosity is lost, quickly heating the ore to meltdown. By contrast, experiments have shown that gas can bypass a region of reduced pore size given an alternative flow path of higher permeability. Therefore, it was decided to examine the meltdown of an ‘ore’ layer surrounded by ‘coke’ slits. The changing structure of the ore layer and its permeability relative to the adjacent coke was considered central to understanding cohesive zone behaviour and, in particular, the distribution of gas flows due to its role in reduction and meltdown.

A cylinder of wax (Series III) or solder (Series IV) particles fully surrounded by a packing of glass spheres in a cylindrical bed was chosen to represent the ore/coke-slit system. Similar geometries have been applied in both low and high temperature experimentation aimed at the blast furnace cohesive zone. However, in contrast to these studies, the degree of contraction was not fixed, with the complete range of behaviour from softening to meltdown considered. By isolating a single cohesive mass, layer interactions were avoided. The influence of locally generated liquids on permeability was also minimised by orientating the layer vertically, such that liquids generated in the hotter, lower part of the bed were able to drip directly into the ‘dropping zone’ under gravity.

3. Method

3.1. Setup

Experiments were performed in the insulated cylindrical steel rig of internal diameter 300 mm represented in Fig. 2. A number of threaded tubes provided access for sampling via thermocouples or pressure taps and could be plugged when not in use. Gas entered the base of the bed through a central 50 mm inlet feeding into a T-junction to prevent liquid ingress. Gas exited the bed over the entire cross-section and was then vented through a central 50 mm offtake in the conical lid. Experimental materials were packed above a steel distributor plate with 3 mm diameter holes located 500 mm below the top of the bed. An air heater, consisting of wound kanthal elements in an insulated steel casing, was connected to the bed by a union joint to allow rapid decoupling for quench runs. The base of the bed containing the gas inlet was held in place with clamps and could be quickly removed. An offtake in the base fed through a union joint into a sealed steel container for liquid collection without gas escape.

For Series I and III experiments, paraffin wax and glass ballotini were used as low temperature analogues for ore and coke, respectively. A mixture of two melting point paraffin wax grades (55 and 65°C) with a minimal melting range around 63°C, was cast into 11 mm spheres. The natural colour of the solid wax was white, but spheres were produced in a range of colours for tracing purposes by adding crayon to the molten wax prior to casting. 17 mm glass spheres represented coke. For Series II and IV experiments, ore was represented by ‘plumber’s’ solder (67% lead, 33% tin) with a melting range of 183 to 250°C, while coke was represented by 11 mm glass spheres. Solder was supplied in a rounded, semi-elliptic bar form, with major and minor axis lengths of approximately 12 and 7.6 mm, respectively. This was cut to approximate 15 mm lengths. To achieve the temperatures necessary for meltdown, the bed was sleeved down to a diameter of 150 mm using Morganite insulating tube surrounded by ceramic fibre insulation in order to decrease the required gas flowrate and, therefore, heating capacity.

The lowest layer of each packing, analogous to the dropping zone in a blast furnace, consisted of glass beads to ensure good distribution of gas to the overlying layer of wax or solder prior to softening. A glass bead overburden was packed above the ore layer(s) to provide loading and prevent fluidisation. In single layer meltdown experiments, glass beads were also packed in an annulus surrounding the central ore cylinder, providing a ‘coke slit’ between dropping and lumpy zones. Temperature and pressure distributions were logged continuously throughout a run and saved for later analysis. Temperatures were measured using fibre-glass-insulated K-type thermocouples inserted through the sampling ports or lid according to the experimental plan. Copper tubes fixed inside threaded barbed connectors were
used to sample static pressure in the bed. Readings were taken automatically using differential pressure transducers.

3.2. Plan

Twelve experiments were performed in Series I according to the settings shown in Table 1 and the configurations represented in Fig. 3. This series examined the effect of layer thickness, layer configuration, gas flow rate and gas superheat on flat wax layer meltdown. Four experiments were performed in Series II (Table 1), examining the effect of layer thickness and configuration (Fig. 4) on flat solder layer meltdown. Eight experiments were performed in Series III (Table 1), examining the effect of layer geometry (Fig. 5) on single wax layer meltdown. Two experiments were performed in Series IV (Table 1), examining the effect of layer geometry (Fig. 6) on single solder layer meltdown. Apart from geometry, the base conditions in Series III and IV reflected those in Series I and II, respectively.

3.3. Procedure

The procedure for each experiment was as follows:
– The bed was packed, and thermocouples and pressure taps were properly located, according to the experimental plan.
– Gas flow was set according to the experimental plan and diverted until the air temperature reached steady-state.
– The gas heater was set to the desired setpoint, and data logging of thermocouples and pressure transducers was commenced, when gas flow was introduced to the rig.
– When the majority of wax/solder had melted away, an apparent steady-state was achieved, or the chosen quench point had been reached, the gas heater was stopped followed by the gas flow.
– In the quench runs, the lid and base were quickly removed and the bed repeatedly inundated with cold water and drained.
– Data logging was stopped and the results were saved for later analysis.
– For the quench runs, the rig was allowed to cool to room temperature and then the bed was excavated to retrieve the cohesive mass(es) and undertake structural analysis.

4. Results

4.1. Flat Layer Meltdown

4.1.1. Series I: Wax Experiments

Pressure measured below the wax layer at A1 (see Fig.

Table 1. Experimental plan for Series I to IV.

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Gas Flow (m³/h)</th>
<th>Temp. (°C)</th>
<th>Run Type</th>
<th>Layer Diameter (m)</th>
<th>Layer Height (m)</th>
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<td>I.1</td>
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<td>meltdown</td>
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<td>0.06</td>
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<td>0.06</td>
</tr>
<tr>
<td>I.3</td>
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<td>90</td>
<td>meltdown</td>
<td>0.3</td>
<td>0.04</td>
</tr>
<tr>
<td>I.4</td>
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<td>0.06</td>
</tr>
<tr>
<td>I.5</td>
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<td>90</td>
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<td>0.3</td>
<td>0.04,0.04</td>
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<tr>
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<td>meltdown</td>
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<tr>
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<tr>
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<td>90</td>
<td>quench</td>
<td>1800</td>
<td>0.3</td>
</tr>
<tr>
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<td>240</td>
<td>meltdown</td>
<td>0.15</td>
<td>0.06</td>
</tr>
<tr>
<td>II.2</td>
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<td>240</td>
<td>meltdown</td>
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<tr>
<td>IV.1</td>
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<td>meltdown</td>
<td>0.1</td>
<td>0.135</td>
</tr>
<tr>
<td>IV.2</td>
<td>50</td>
<td>240</td>
<td>quench</td>
<td>4200</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Fig. 3. Packing and sensor configuration for Series I (dimensions in mm).

Fig. 4. Packing and sensor configurations for Series II (dimensions in mm).

Fig. 5. Packing and sensor configuration for Series III (dimensions in mm).

Fig. 6. Packing and sensor configurations for Series IV (dimensions in mm).

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3), and temperatures measured below (A1), within (A2) and above (A3) the layer in Run I.1 are shown in Fig. 7. In general, the form of the pressure plot was representative of experiments in Series I. Pressures were steady during initial heating, but increased sharply upon initial softening of the wax layer. This increase was only arrested once gas channels began to form through the wax. Subsequently, pressures decreased and stabilised, but at levels higher than the initial packing, during a period of steady meltdown. A further distinct drop in pressure did not correspond to complete meltdown, but was linked to liquid holdup phenomena. At this ‘drainage transition’, liquid, which had earlier accumulated on the melting layer, was able to descend once sufficient channel meltdown had occurred to decrease the level of gas–liquid interaction.

Temperature measured below the wax layer increased steadily towards a maximum determined by the heater setpoint and heat losses from the system. However, as permeability was lost, temperature within the wax at A2 arrested below the melting point. This was attributed to isolation of the thermocouple from the gas stream by compression of the surrounding wax, with all subsequent heat transferred to the layer consumed by fusion at the surface. Temperature above the layer at A3 exceeded that at A2 for a significant period until sufficient meltdown had occurred to re-expose the latter to the gas stream. Channelling of gas and heat to the upper part of the bed represented an under utilisation of smelting capacity within the cohesive layer.

In Runs I.1 and I.2, the maximum pressures were markedly different despite similar operating conditions, as shown in Fig. 8. This was attributed to the variability associated with channel formation since the remainder of the pressure plots, including the time to softening, steady meltdown and the drainage transition, were very similar, demonstrating some repeatability in the meltdown behaviour. However, temperatures measured within the wax layer at A2 remained different long after channel formation had occurred. While the thermocouples were located in the same position in the layer, it was apparent that the gas channels were not, indicating that the geometry of meltdown could not be predicted.

Figure 9 illustrates the effect of layer thickness and configuration on meltdown. For the thin layer in Run I.3, the magnitude and duration of the pressure peak were relatively low, as was the pressure during steady meltdown and the time to the drainage transition. Doubling the layer thickness in Run I.4, the duration and, in particular, magnitude of the pressure peak were increased, indicative of more difficult channel formation. Pressure during steady meltdown and the time to the drainage transition also increased, consistent with the thicker region of low permeability and increase in material to be melted. The thermocouple at A2 in Run I.4 was well embedded in the cohesive wax, with a very stable period of thermal arrest below the melting point.

In Run I.5, the same mass of wax used in Run I.4 was split into two layers of mass equal to Run I.3 separated by a 100 mm ‘coke slit’. A double pressure peak of maximum amplitude similar to Run I.3 marked the channel formation period, suggesting that softening and gas breakthrough occurred separately for the two layers. However, the steady meltdown period was reached soon after Run I.4 at approximately 1 700 s and the drainage transition just before at 2 200–2 400 s, consistent with a similar total mass for meltdown. Therefore, splitting the layer was not found to be strongly advantageous for reducing the period of meltdown of a flat layer, but did improve channel formation and layer permeability.

In Runs I.6 and I.7 (Fig. 10), gas flow rate was decreased and increased by 50 m$^3\cdot$h$^{-1}$, respectively, compared with Runs I.1 and I.2. Prior to softening, pressures were found to increase with gas flow rate. The time to softening was decreased due to faster heating. No apparent trend was found in the maximum pressure achieved prior to channel formation. However, increasing the gas flow rate shortened the
period from softening to the formation of a stable channel structure, possibly due to higher gas drag ‘stripping’ generated liquids away from gas flow paths through the wax more rapidly. Increased gas flow rate and liquid holdup were both thought to contribute to the differences in pressure during steady meltdown.

In Runs I.8 and I.9 (Fig. 11), the gas temperature was decreased and increased compared with Runs I.1 and I.2, respectively. The maximum pressure achieved prior to channel formation, and the period of softening and channel formation, decreased with increasing gas temperature. This was associated with an increased rate of liquid generation and superheating. Faster meltdown would allow gas channels to expand more rapidly, while increased superheat would improve the fluidity and removal of wax from the meltdown site. Increasing gas temperature between Run I.8 and Runs I.1 or I.2 halved the period between the commencement of softening and the drainage transition (from approximately 2 300 to 1 100 s). The pressure during steady meltdown was higher at lower gas temperatures. This may reflect the difficulty and therefore extent of channel formation, or increased liquid viscosity and, therefore, liquid holdup at lower temperatures. As for gas flow, the period of thermal arrest at A2 was found to increase with a decrease in heat input to the bed.

In Runs I.10 to I.12, experiments performed under the same conditions as Runs I.1 and I.2 were quenched at a chosen point in time to capture the mid-run structural characteristics. Run I.10 was stopped after 1 400 s, corresponding to the start of the steady meltdown period, and quenched with water. At this stage, a single major gas channel had developed near the edge of the layer, which was otherwise well compacted with no visible porosity for gas-flow. Molten wax, at least partially sourced from the lower levels of the layer, had undergone considerably more meltdown than Run I.10. The cohesive mass was wedge-shaped (Fig. 12), with meltdown occurring at a major gas channel established at the wall (left-side in Fig. 12). Adjacent to the channel, the layer had thinned considerably indicating that meltdown was fastest in the region of highest gas velocities, i.e. convection driven. An uneven buildup of resolidified wax, distributed away from the gas channel, was again present on the upper surface. Its colouration indicated mixing of upflow from all heights of the layer due to meltdown at the channel edge and the lower surface.

Despite being quenched at the same point in time as Run I.11, the structure of the wax layer was quite different in Run I.12 due to the variable nature of channel formation. In addition to a major channel adjacent to the wall, there was one formed near the centre of the bed. Once such stable channels are formed, the pattern of gas flow and layer meltdown is firmly established due to compaction and impermeability of the remainder of the layer. Runs I.12 and I.11 can be used to interpret the temperatures measured at A2 in Runs I.1 and I.2, respectively (Fig. 8). Minimal meltdown from a central gas channel, as in Run I.12, would be required to expose an axially located thermocouple embedded in the wax, resulting in rapid heating, as achieved in Run I.1. Much greater meltdown would be required to reach the central thermocouple from an edge gas channel, as in Run I.11, resulting in gradual heating, as achieved in Run I.2.

4.1.2. Series II: Solder Experiments

The general meltdown behaviour of flat solder layers in Series II differed in some respects from that achieved for wax in Series I, although the pressure was still characterised by periods for heating, softening and channel formation, and stable meltdown. While all runs in Series II were classified as meltdown experiments in Table 1, temperatures were not sufficient to achieve complete meltdown, with tin-rich liquid dripping away above the eutectic temperature and forcing up the final melting point. Consequently, a residual cohesive mass was recovered from the rig after each run.

Pressure measured below the solder layer at A1 (see Fig. 4), and temperatures measured below (A1), within (A2) and above (A3) the layer in Run II.1 are shown in Fig. 13.
Temperature below the solder layer was found to increase gradually, pausing at around 210°C during softening and channel formation (4 000 s) before approaching a steady temperature of around 240°C at 8 000 s. The pressure remained steady until approximately 3 500 s before increasing sharply. At that point, temperature in the solder had steadied close to the eutectic at 188°C, prior to the thermocouple failing. Therefore, softening was linked to liquid generation, rather than compaction of the solid. The formation of liquid led to a loss of structural strength in the solder particles and partial collapse of the packing, increasing the resistance to gas flow. The pressure continued to fluctuate at elevated levels while a quasi-steady structure and pore network was established through the remaining solder. Between 4 000 and 5 000 s, the pause in temperature rise at A1 (Fig. 13) finished as the heat demand for melting eutectic liquid was satisfied. At the same time, the pressure drop steadied and entered a period of gradual decline associated with ongoing meltdown.

After cooling Run II.1, the rig was emptied and the residual solder recovered. Like the wax meltdown experiments in Series I, the cohesive mass appeared to be predominantly impermeable apart from a discrete number of channels. Two major channels were identified, one adjacent to, and the other slightly away from, the wall. A resolidified solder stalactite accompanied the first, indicating that meltdown was occurring in the region of high gas flow. There was minimal evidence of the original solder packing, and deformation had left an impression of the underlying glass beads in the lower surface. Due to the high density of the solder, there did not appear to be liquid accumulation on the upper surface, thus explaining the absence of the drainage transition in the pressure plot. Without accumulation, there was no shrouding of the channel walls with liquid to retard meltdown as was the case with wax. Therefore, the channel area increased steadily with meltdown, gradually decreasing the resistance of the bed and the pressure drop over time.

Prior to thermocouple failure at A2, temperatures above the solder at A3 had risen above that within the layer. Like Series I, this was attributed to isolation of the thermocouple from the gas stream during the softening process. However, due to the superior thermal conductivity of solder, the arrest temperature was close to the eutectic at which liquid was generated at the solder-glass interface surrounding the solder ‘slab’. This compares to Series I where the low thermal conductivity caused the temperature within the wax to arrest below the melting temperature, with all transferred heat consumed at the wax surface by fusion. Unlike Series I, the effect of fusion on gas temperature leaving the cohesive layer was illustrated by the depressed heating rate at A3 during softening and channel formation. Although faster convective heat transfer in Series II may have caused this, no definite conclusions could be drawn due to differences in the rates of heating.

Figure 14 superimposes temperatures at A2 and pressures at A1 as a function of layer thickness and configuration using data from Runs II.2 to II.4. Prior to softening, the gas pressure drop was found to be a function of solder mass, increasing from the 40 mm layer in Run II.2 to the 80 mm layer in Runs II.3 and II.4. Although the total bed thickness also increased, the magnitude of the change indicated that the unconsolidated solder provided a greater resistance to gas flow than the glass beads. Upon softening, pressures increased rapidly, but to relatively low and similar average levels during channel formation when compared to the equivalent wax meltdown runs in Series I. The change in behaviour was partly attributed to the increased density of molten solder that aided its removal from meltdown sites and prevented accumulation and plugging of gas channels. Additionally, once eutectic liquid had been removed from the layer, remaining solder had superior structural strength to wax, thus resisting compression under load and the collapse of gas channels.

The period of channel formation was found to be dependent on the mass of solder, taking around 2 000 s in Run II.2, and 3 000 s in Runs II.3 and II.4. Similar to the wax experiments (Run I.5), splitting the same mass of solder as Run II.3 into two layers separated by a coke slit in Run II.4 caused a double pressure peak, due to separation of their channel formation stages. This double peak was distinguished from secondary pressure peaks in Runs II.1 and II.3 by the corresponding double arrest in the temperature measured at A2. Subsequent to channel formation, the pressure during steady meltdown was found to increase with layer thickness between Runs II.2 and II.3, with an intermediate level of permeability achieved in Run II.4.

Differences in permeability during the latter stages of meltdown were consistent with the structures of cohesive masses recovered from Runs II.2 to II.4. For the thin 40 mm layer in Run II.2, channel formation was relatively easy, with numerous gas flow paths established within the layer and adjacent to the wall, as shown in Fig. 15. By doubling the layer thickness in Run II.3, it was more difficult for gas...
to establish flow paths through the collapsing structure, with the major gas channel formed adjacent to the wall, as shown in Fig. 16. Therefore, pressure drop across the thicker layer was higher due to the increased channel length and decreased flow area for gas. In Run II.4, gas only had to establish flow paths through separate 40 mm layers, so a larger flow area than Run II.3 was established. However, pressure drop was higher than Run II.2 due to the presence of two cohesive masses.

4.1.3. Summary

Using wax or solder as an experimental analogue for ore, the effect of gas flow rate, temperature, and layer thickness and configuration on the meltdown of flat layers was examined. Decreasing gas flow rate or superheat, or increasing layer thickness increased the time required for meltdown due to a decrease in the ratio of heat input rate to total latent heat of melting demand. Decreasing the ore layer thickness by increasing the number of layers improved channel formation and permeability, but not necessarily the rate of meltdown, when the cohesive zone was flat and gas was not forced to flow along coke slits. Apart from the variable nature of channel formation observed through pressure measurements and quenching, the meltdown behaviour was found to be reproducible, with periods for heating, softening and channel formation, and steady meltdown.

Irrespective of material type, flat layer meltdown was characterised by the formation of a limited number of gas channels upon loss of permeability due to softening. The location and number of these channels could not be readily predicted, though the latter appeared to decrease with an increase in layer thickness. Once flow paths were established, permeability stabilised and meltdown proceeded with gas flow and, consequently, heat transfer and liquid formation, maldistributed across the layer. Due to this maldistribution, the meltdown of intermediate cohesive masses was retarded.

4.2. Single Layer Meltdown

4.2.1. Series III: Wax Experiments

Conditions for experiments in Series III were identical to those in Series I of the flat layer experiments except for the configuration of the wax. Using an array of 19 thermocouples (Fig. 5), the bed temperature distribution in Run III.1 was plotted at 10-min intervals assuming axisymmetric conditions, as shown in Fig. 17. For simplicity, the 9 flexible thermocouples located in the wax were assumed to remain at fixed positions throughout a run, allowing them to be assessed relative to the location of the original wax layer. Commencing from ambient temperature (25°C), the bed was heating rapidly and relatively uniformly across the radius after 10 min. Slower heating of the wax was attributed to preferential gas flow near the wall due to increased porosity and the change in particle size from 11 to 17 mm between wax and glass. Temperatures within the wax had not reached the melting point at that stage.

After 20 min, temperature maldistribution across the radius was more pronounced, with the 65°C isotherm, in particular, clearly affected by the location of the wax. This was linked to the onset of melting between 60 and 65°C causing a collapse in the pore network through the lower part of the wax layer and forcing gas towards the wall. With gas flow diverted towards the wall, the temperature gradients in the wax layer were found to change from predominantly axial in the early stages of heating to perpendicular to the wax–glass interface (i.e. axial at the base and radial at the sides of the wax layer), with gas channelling up the wall and isotherms ‘wrapping’ around the wax layer, as shown between 30 and 50 min. A melting ‘front’ was assumed to accompany this heating, with gas access to the wax progressively retarded by structural change at the interface. The cool region appearing adjacent to the wall near the base of the wax layer was attributed to measurement error.

By 70 min, gas temperatures of at least 80°C were measured below, beside and above the wax. However, the temperature in the core of the wax layer was still well below the melting point at less than 55°C. In fact, temperatures below the melting point were observed for a further 60 min, during a period of thermal arrest. During this time, the size of the wax layer was assumed to shrink by meltdown at the glass–wax interface, as represented by the encroachment of high-temperature isotherms into the original boundary of the wax from the sides and above. Although melting at the lower interface was expected, the downward movement of solid wax under gravity to replace melted material and the insulating effect of molten liquids from higher levels were found to ensure longevity of the wax in this region. The melting temperature of the wax was finally exceeded throughout the bed after 140 min, with rapid heating to near uniform temperatures following, as shown after 150 min.

Figure 18(b) plots time isopleths, in minutes, to reach 65°C in Run III.1. This temperature was chosen to exceed the melting point of 63°C and, therefore, represent the motion of the melting interface through the wax. The contours reveal the axial nature of heating in the early stages, the channelling of gas through the coke slit and around the
wax, and the delayed melting of the wax core. Figs. 18(a) and 18(c) demonstrate the effect of decreasing and increasing gas flow rate in Runs III.2 and III.3, respectively. The rate of bed heating was found to increase, and longevity of the wax core decrease, with increasing gas flow rate. The effect of increasing gas superheat from Run III.4 to III.5 was similar, as shown in Fig. 19.

In Runs III.6 to III.8, experiments performed under the same conditions as Run III.1 were repeated to different stages then quenched in order to try and capture the mid-run structural characteristics. The bed temperature distributions prior to quenching are shown in Fig. 20. For Run III.6, which was stopped after 1 800 s, temperatures near the melting point were observed at the base and sides of the layer, but a cooler region of less than 50°C was still present at the top. This corresponded closely to the recovered structure that had a fused shell at base and sides and unconsolidated particles in the central part of the upper surface. The localisation of fusion at the boundary, consistent with thermal arrest below the melting point in the interior, was revealed by splitting the cohesive mass across the diameter. Apart from the base and sides, particles were readily distinguishable throughout the layer.

Increasing the quench time to 3 900 s in Run III.7 and then 5 400 s in Run III.8 shifted the coolest part of the bed, at less than 50 and 55°C, respectively, towards the centre of the wax. Additionally, isotherms above the melting point were found to have encroached into the wax region on all sides. This was accompanied by total enclosure of the wax layer within a fused shell. A vertical cross-section through the wax in Run III.7 revealed an increased level of compaction, but particles were still distinct and porosity remained, as shown in Fig. 21. Even after a significant period of further meltdown at 5 400 s, a similar structure was found within a thin fused shell in Run III.8.

Using the initial packing size, measurements of the three quenched specimens and an estimate for complete meltdown, the change in layer dimensions with time was plotted in Fig. 22 along with the bed pressure at A1 in Run III.1. Meltdown caused the pressure to increase, but not to the extent seen in the flat layer meltdown experiments due to the maintenance of permeability through the ‘coke-slit’. Complete meltdown was estimated at 8 665 s from the point at which all thermocouples exceeded the wax melting point in Run III.1. The decrease in height was attributed to both compaction and meltdown, while the decrease in radius was from meltdown alone. Therefore, height decreased faster than diameter in the early stages of softening. However, while the rate of change in height appeared relatively constant, the rate of change of diameter increased with decreasing diameter. Based on the observation that heat transfer and meltdown were localised at the melting surface, this was consistent with the surface area to melting volume ratio.
in the two directions. As the layer diameter decreased, there was a gradual decline in pressure due to improved permeability through the enlarged coke slit.

4.2.2. Series IV: Solder Experiments

To examine the effect of increased conductivity on meltdown, solder (thermal conductivity around 40 W·m⁻¹·K⁻¹) was substituted for wax (0.25 W·m⁻¹·K⁻¹) in a second series of single layer experiments. Conditions in Series IV were identical to those in Run II.1 of the flat layer meltdown experiments except for the configuration of the solder layer. Using an array of 13 thermocouples (Fig. 6), the bed temperature distribution from Run IV.1 was plotted at 10-minute intervals, as shown in Fig. 23. The pattern of heating was similar to the wax meltdown experiments, with a uniform radial distribution of temperature up to 50 minutes followed by faster heating at the periphery of the solder between 60 and 80 minutes. The latter was associated with meltdown and structural change of solder upon reaching the eutectic temperature. However, unlike the wax, an extended period of thermal arrest was not observed, with the radial temperature distribution equalising between 90 and 100 minutes despite the continued presence of a cohesive mass. This suggested that, if the cohesive mass was found to be impermeable at the surface, thermal conductivity must have been a significant contributor to heat transfer following initial softening.

The structure of the partially softened solder was clarified by quenching Run IV.2 after 70 min, during the period in which a significant radial temperature distribution had developed in Run IV.1. Like Run III.6, the recovered mass had formed an impermeable shell at base and sides, within which unconsolidated particles were still present and exposed at the top surface, as shown in Fig. 24. However, unlike the wax, the shell appeared to be relatively thick, with numerous solder particles deformed and welded together near the surface. This suggested that superior thermal conductivity was transferring heat inward from the solder–glass interface, rather than all energy being consumed by fusion at the interface. Furthermore, by examining the cohesive mass recovered at the end of Run IV.1, it appeared that the remaining unconsolidated particles were progressively softened from the base and sides, rather than the top, since the final shape consisted of a thick, open-topped shell, as shown in Fig. 25. Since the base and sides were found to be impermeable, thermal conductivity must have played an important role in the heat transfer to, and therefore meltdown of, the solder consistent with the minimal period of thermal arrest.

4.2.3. Summary

Single layer meltdown experiments illustrated the progression in softening-melting behaviour along a cohesive layer imbedded in a permeable packing. Irrespective of material type, meltdown was characterised by loss of permeability at the layer surface and distribution of gas flow to the surrounding coke. Subsequently, convective heating could only occur at the ore-coke interface, with heating inside the layer dependent on thermal conduction. Meltdown proceeded from the interface, but was hindered by the retention of voidage within the layer. Using wax as an experimental analogue for ore, decreasing gas flow rate or superheat was found to be detrimental to the efficiency of meltdown. Increasing the thermal conductivity of the ore by using solder was found to decrease the extent of thermal arrest and improve the transfer of heat to the layer through impermeable interfaces. Unlike the flat layer experiments, gas pressure drop, and therefore meltdown behaviour, was relatively stable and predictable throughout a run due to the presence of the permeable packing between dropping and lumpy zones.

5. Application of Results

When the cohesive zone profile was flat, the path of gas between lower and upper furnace and, consequently, the path of liquid from cohesive zone to hearth, could not be readily predicted. This introduced variability into the meltdown process. Therefore, for operational stability and to enable furnace behaviour to be modelled and controlled, there is a requirement to maintain sufficient radial non-uni-
formity in the ore-to-coke distribution to ensure the development of coke slits through the cohesive zone. In fact, flattening the cohesive zone to improve gas utilisation may prove counterproductive, due to the promotion of gas channelling. Channelling and variability should be considered when interpreting the results of high temperature softening-melting tests, since these employ a similar flat layer configuration.

Structural changes in wax and solder packings represented two extremes of softening behaviour. Wax was characterised by low compressive strength and deformation under load prior to formation of a relatively viscous, low density liquid, while solder resisted deformation prior to formation of a relatively dense, low viscosity liquid. Likewise, poorly reduced ore that forms a high volume of viscous primary slag would deform significantly prior to the free flow of liquid, whereas metallic iron in well reduced ore will form a strong structure to resist deformation while liquid is generated. Apart from limiting permeability loss to the true melting range of the material, solder was superior to wax because of a lower level of interaction between the liquid product and gas. Similar benefits in the blast furnace are dependent on maximising the level of indirect reduction and minimising the slag volume.

Isolating a single layer for meltdown and changing the geometry to minimise deformation under load and liquid accumulation, it was possible to observe non-uniform structural variation through a cohesive layer. Heating of the layer changed from direct gas-particle heat transfer to heat transfer at the ore–coke interface in combination with conduction to the core as permeability at the interface was lost by meltdown. Meltdown continued along the interface via heat transfer from the gas flowing through the coke slits. Much of the heat transferred to the layer was consumed by fusion at the interface and a temperature gradient developed through the layer. Consequently, a shell of softened material was formed, protecting the core from gas flow, while retained porosity in the core limited the thermal conductivity. The importance of conductivity after softening, and a further advantage of increased indirect reduction, was demonstrated by the decreased extent of thermal arrest and improved heat transfer through impermeable interfaces of solder compared to wax.

In terms of blast furnace modelling, the findings were principally concerned with the physical description of the cohesive zone. The structural transition of an ore layer from unconsolidated particles to a cohesive slab, and the associated change in contribution to heat transfer of convection and conduction, have previously been established. Associated with the loss of permeability would be retarded heating of the ore and the potential for a significant temperature gradient between surface and core. These were thought to contribute to the significant correction factors on heat transfer employed in a number of blast furnace models. The temperature gradient between ore and coke should be considered, either directly, by separating enthalpy equations, or indirectly, using the modified heat transfer coefficient of Stuke or similar. The latter has been applied to the heating of particles in the blast furnace, but would be more significant for an impermeable cohesive slab.

\[ h'_{gs} = \frac{h_{gs}}{1 + h_{gs}L_o/6k_o} \] ..........................(1)

where \( h'_{gs} \) is the modified heat transfer coefficient, \( h_{gs} \) the heat transfer coefficient at the interface, \( L_o \) the layer thickness and \( k_o \) the layer thermal conductivity. Two key parameters for heat transfer in the cohesive zone that appear in Eq. (1) are the thermal conductivity of the cohesive slab and the heat transfer coefficient at the interface. Use of the thermal conductivity of the cohesive liquid material, as proposed by Gudenau et al., is recommended for the former, based on experimental observations of significant liquid flow through the cohesive zone. Previous blast furnace models have represented the latter as heat transfer between gas flowing through a packed bed and an adjacent smooth surface. However, conditions in the blast furnace are unique, with a non-uniform interface, and interpenetration of ore and coke particles. This was identified as an important area for future study, with no relevant equations identified in the open literature.

6. Conclusions

An experimental study was undertaken to examine the meltdown of burden materials in the blast furnace. The meltdown of flat cohesive zones was characterised by variability and gas channelling, promoting furnace instability and preventing accurate modelling. The meltdown of single layers demonstrated the possibility of structural variation between the surface and core, and the change in contribution of convection and conduction to heating. Use of experimental materials of significantly different physical properties illustrated a range of potential softening behaviour, and emphasised the importance of maximising indirect reduction and minimising slag volume for blast furnace performance.

REFERENCES