DETERMINATION OF THERMAL CONDUCTIVITY OF RECOVERY BOILER CHAR BED MATERIALS

by

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A thesis submitted in conformity with the requirements for the degree of Master of Applied Science
Graduate Department of Chemical Engineering and Applied Chemistry
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ABSTRACT
Heat transfer within a char bed of a recovery boiler used in pulp and paper mills is important in determining the cooling rate of a char bed following an emergency shutdown. The rate of heat transfer depends on the thermal conductivities of frozen smelt and char, but there is little reliable data available on these thermal properties.

An experimental apparatus was thus built to measure the thermal conductivity of various char samples made in the laboratory and collected from operating recovery boilers, under normal operation and following an emergency shutdown procedure. The reliability of the apparatus and measurement method was first verified using firebricks with known thermal conductivity values and a numerical simulation.

The thermal conductivity of char bed materials with different porosity and structure was found to be constant up to 500°C and then increase linearly with the temperature. Based on the data, a two-part correlation is recommended to predict the effective thermal conductivity of char bed materials with various porosity (between 55% and 80%) and structure:

For \( T \leq 500°C \) \( k_{\text{eff}} (\text{W/m°C}) = 0.21 \)

For \( T > 500°C \) \( k_{\text{eff}} (\text{W/m°C}) = 0.0035 \times T (°C) - 1.54. \)
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NOMENCLATURE

A   cross sectional area, m$^2$

$C_p$ specific heat of material, J/g°C

D, d diameter, m

$\frac{dT}{dt}$ rate of temperature change, °C/s

$\frac{dT}{dx}$ temperature gradient, °C/m

g acceleration due to gravity, m/s$^2$

Gr Grashof number

h average convection heat transfer coefficient, W/m$^2$K

k thermal conductivity, W/m°C

L vertical height, m

m mass of material, kg

$Nu_L$ average Nusselt number

Pr Prandtl number

q heat flux, W/m$^2$

Q heat flow rate, W

$Ra_L$ Rayleigh number

T temperature, °C (K)

$\Delta T$ temperature difference, °C

$\Delta x$ difference in location, m

$\phi$ porosity

E exchange factor
\[ \beta \] volumetric thermal expansion coefficient, K\(^{-1}\)

\[ \nu \] viscosity (m\(^2\)/s)

\[ \sigma \] Stefan-Boltzman constant. \( \sigma = 5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4 \)

\[ \sigma = 0.1714 \times 10^{-8} \text{ BTU/hr.ft}^2\text{°R}^4 \]

**Subscript**

- b: bed
- c: calorimeter
- cond: conduction
- eff: effective
- f: furnace
- in: inlet
- out: outlet
- p: pore
- r: radiation
- s: surface
- w: water
- Z-B-S: Zehner-Bauer-Schlunder
- \( \infty \): surrounding
Recovery boilers are used in the pulp and paper mills to recover inorganic materials used during the pulping process and also to generate steam for the plant. Black liquor, which is the by-product of chemical pulping, is burned in recovery boilers. The combustion of black liquor converts the organic constituents of the liquor into gaseous products in a series of processes involving drying, pyrolyzing, char gasification, and finally combustion in the furnace. Burning of char, the residue left after pyrolysis occurs largely on the char bed which covers the floor of the furnace. As the carbon in the char is burned, the inorganic compounds in the char are released and form a molten salt mixture called smelt that flows to the bottom of the furnace and out of the boiler through smelt spouts (Adams et al., 1997).

Smelt produced from a kraft recovery boiler consists of approximately two-thirds Na₂CO₃, and one-third Na₂S. small amounts of Na₂SO₄, other sodium/sulfur compounds, and unburned carbon (Adams et al., 1997). Different chemical recovery processes and boiler operating strategies are used by the industry; however, one common feature of all recovery boilers is that water must never come into contact with a hot char bed. Molten smelt reacts violently with water generating destructive detonation waves. The mechanical energy generated in a recovery boiler explosion has been compared to explosions of about 1 to 5 kg of TNT. There have been over 140 reported recovery boiler explosions in North America. In some cases injury and even death of personnel have occurred (Grace, 1999; Green, 1992).
The recovery boiler is immediately shutdown if any water is suspected to have entered the combustion chamber. The emergency shutdown procedure (ESP) involves stopping the firing of black liquor, draining of water from the boiler tubes, and shutting off the water feed to the boiler. This leaves a residual bed consisting of hot char, molten smelt, and frozen smelt (Figure 1-1), which has to be cooled down sufficiently so that water-washing of the furnace floor can be safely performed.

Figure 1-1  Char bed left on the hearth of a recovery boiler a) following an emergency shutdown, b) hot pockets in the char bed.

There is little known about the cooling mechanisms of the char bed following an ESP, therefore the boiler shutdown can last up to a few days. This downtime costs the industry approximately $20,000 per hour in lost production. It is estimated that about 100 emergency shutdowns occur per year worldwide. Hence, there is a considerable economic benefit in understanding the heat transfer mechanisms governing the cooling of char beds following an ESP and avoiding unnecessary downtime. Heat transfer within char beds also determines the extent that chemical
reactions proceed beneath the bed surface and the magnitude of heat transfer rates to floor tubes. Thus, the processes that occur during cooling of the char bed following an ESP are quite complex; however, the main heat removal mechanism is by conduction heat transfer to the floor tubes.

While the bed heat transfer depends greatly on the thermal conductivity of smelt and char materials, there is little reliable data available on this important property. The only source of information on the thermal conductivity of char bed materials and smelt is from a report by Richardson and Merriam of Arthur D. Little Inc. (ADL), (Richardson and Merriam, 1977). They attempted to measure the thermal conductivity of char beds in several operating boilers but many questions have been raised recently about the measurement techniques they used (Kawaji et al., 1999). Nevertheless, Richardson and Merriam (1977) recommended a model to predict the thermal conductivity of char at high temperatures. This thermal conductivity model, however, has not been verified by more reliable measurements.

1.1 Objectives

The objectives of this study were as follows.

1. Construct an experimental apparatus to accurately determine the thermal conductivity of char bed materials.

2. Make direct measurements of the thermal conductivity of char bed materials from different recovery boilers.

3. Study the effects of temperature, porosity, and structure on the thermal conductivity of char bed materials.
4. Using the data obtained, verify Richardson and Merriam’s correlation for the char thermal conductivity. If this correlation cannot adequately represent the data, propose a new correlation to predict the thermal conductivity of char bed materials at different temperatures.
General recovery boiler design and operation, and char bed characteristics known to date will be discussed in this chapter. Also, char bed properties measured by Richardson and Merriam (1977) and their experimental methodology, as well as some general procedures for measuring the effective thermal conductivity of porous materials will be covered.

2.1 Recovery Boiler Design and Operation

As mentioned in Chapter 1, recovery boilers are used in pulp and paper mills for two main purposes: firstly to recover the inorganic chemicals used during the pulping process; and secondly to generate steam for the plant by making use of the chemical energy present in the organic portion of the black liquor.

Black liquor contains all the inorganic chemicals and other organic materials that separate from the wood during the pulping process. The initial concentration of dry solid in black liquor is about 15%. It is concentrated to 65% to 85% dry solids before firing (Adams et al., 1997).

In the furnace of a recovery boiler, combustion converts organic materials into gaseous products such as carbon monoxide (CO) and carbon dioxide (CO₂). As the carbon in the char is gasified, molten smelt is released which flows to the bottom and out of the through smelt spouts (Adams et al., 1997).

Under normal operating conditions, black liquor is injected through liquor guns into the recovery boiler (Figure 2-1).
At the same time hot air is blown into the furnace through air ports. As a result, most of the water in the black liquor evaporates off. The presence of air causes the gasified carbon and some of the pyrolysis gases to burn in the region above the char bed. This combustion releases a large amount of heat that melts the inorganic compounds. The inorganic materials and the unburned carbons drop to the bottom of the furnace. The char (unburned-solid-carbon) is a very porous and flaky material with a very low density. The molten smelt has a higher density and thus flows to the bottom of the furnace. This causes the char to form a bed on top of the smelt (Figure 2-2).
2.1.1 Lower Furnace Construction

The furnace walls are constructed from a series of vertical tubes carrying boiling water (Figure 2-3). These tubes are typically 6.4 to 7.6 cm in diameter. In modern construction the tubes are spaced about 1.25 to 2.5 cm apart and are connected by a flat fin. This is called the membrane construction. Four rows of vertical tubes form the furnace walls and are referred to as the waterwalls. Heat is transferred to the water flowing in the tubes by radiation from the char bed and flames in the furnace. The furnace waterwalls represent as much as one half of the heat-transfer surface area required to generate high pressure steam (Adams et al., 1997).
Waterwall tubes in the lower furnace are exposed to a very hostile environment. In the lower furnace the smelt/char bed temperature can reach up to 830°C. In this region, tube wall corrosion by molten deposits is unlikely since a protective layer of frozen smelt forms on the outer surface of the water tubes and usually tube temperature does not exceed 350°C. Above the char bed, however, a flue gas containing a corrosive, reduced sulfur species exists at temperatures of about 1000 to 1250°C. Sulfidation by reduced sulfur gases is the main cause of tube thinning, since partial pressure of O₂ in the lower furnace is insufficient to stabilize Fe₃O₄ on the tube surface. Tubes removed from recovery boilers usually show a thick FeS scale on the surface and no detectable iron oxide. The corrosion rate is typically less than 0.2 mm/year but can be as high as 0.8 mm/year. The severity of corrosion increases with tube surface temperature.

Figure 2-3  Lower furnace arrangement with composite tube wall construction (Adams et al. 1997)
and to a lesser extent, with the concentration of sulfur gases. In order to make the waterwalls more resistant to corrosion, composite tubes are used. These tubes are made with a stainless steal sheath on the outside of a carbon steel tube (Adams et al., 1997).

2.1.2 Char Bed Characteristics

Black liquor recovery boilers operate with char beds at the bottom of their furnaces. As mentioned before, char beds consist of carbon, partially pyrolyzed black liquor solids, and molten and frozen smelt. Char beds come in various shapes such as low, flat beds, and crater-shaped beds. Some beds can be as high as 3m (Adams et al. 1997).

Under ideal conditions, all the inorganic pulping chemicals in the black liquor would reach the bed and separate from the burning char and flow out of the smelt spouts without being oxidized. The carbon in the char would burn to form CO and CO₂, or would react to form Na₂CO₃, and the sulfur would be converted to Na₂S. The role of the char beds is to provide an environment for these chemical reactions to take place. It provides a surface for air/carbon contact, and a reducing environment to protect sulfide in the molten smelt from being re-oxidized to sulfate (Green, 1992).

Despite the central role of the char bed in the stable, efficient, and safe operation of the recovery boiler, it is one of the least understood parts of the overall process. There is relatively little field data on char bed properties compared to other parts of black liquor combustion process. In the past several years the use of bed imaging cameras in addition to laboratory and computer studies of char burning and bed cooling has increased the knowledge of bed characteristics (Grace, 1998).
The size and shape of a char bed are determined by boiler design, firing technique, air delivery, and the combustion properties of the black liquor fired. The following description of char beds was developed by Richardson and Merriam (1977) as a result of an Arthur D. Little Inc. (ADL) study.

In most recovery boilers, the char bed is believed to consist of a hot, active burning layer at the bed surface supported by a colder, inactive bed at the bottom. The active layer is typically 15-20 cm thick. The temperature of the active layer decreases with distance into the bed from 1000-1200°C at the surface of the bed to 760°C at the bottom of the active char layer where smelt has solidified. The solid carbon in the active char layer provides structure even though the char mass is mostly molten smelt. Below the active layer there is the denser and chemically inactive core of bed that is below the inorganic melting point. This has a thermal conductivity similar to that of a good insulator. The physical characteristics of the active layer in char beds are similar in all types of recovery boilers. On the other hand, the characteristics of the inactive layer differ with boiler types. These differences affect the flow of molten smelt from the char bed to the spouts and the amount of smelt within the boiler (Richardson and Merriam. 1977).

Two different types of recovery boiler include the slanted floor boiler, and the decanting hearth boiler (Figure 2-4). The char beds in slanted-floor boilers are usually a single mount with a relatively flat top. The height of the bed is limited by air injection at the secondary air port. The inactive part of the char bed in these boilers is quite dense and far less permeable than the active char layer. Smelt collects in troughs around the perimeter of the bed and in channels through the bottom of the bed to the perimeter. On the other hand various shapes of char beds are observed in decanting-hearth boilers. The beds are usually low, with molten smelt under most of the bed. The char characteristics in the inactive bed are quite different from those in slanted-floor boilers. The
char is very porous and mobile. Temperature measurements within these char beds show that the smelt is molten throughout the bed. Thus the beds sit in a pool of molten smelt that is contained by the decanting bottom of the boiler, with a layer of solid smelt above the floor tubes (Adams et al., 1997).

Figure 2-4  Schematic diagrams of char bed near a smelt spout in slanted-floor and decanting-hearth recovery boilers (Adams et al., 1997).
2.2 Smelt-Water Explosion

There have been over 140 recovery boiler explosions reported in North America due to smelt-water contact. The damages caused by these explosions range from complete destruction of the boiler to negligible damage (Green, 1992). In some severe cases, injury and even death of the personnel have occurred. There are an estimated 100 ESP’s per year worldwide where the fear of explosion leads to a prolonged shutdown of the boiler (Grace, 1999).

One general rule that applies to all recovery boilers is that water must never contact the char bed, because there can be an explosive reaction between water and molten smelt. This is a physical reaction in which water evaporates rapidly when it contacts the hot smelt. This results in rapid steam expansion generating highly destructive detonation waves. Smelt-water explosions are unique to recovery boilers and are the most common type of explosions encountered. Smelt-water explosions can occur any time when sufficient amounts of molten smelt and water come into contact with each other. The mechanical energy generated by evaporation of 0.45 kg (1 lb.) of water in 0.001 second is estimated to be equivalent to that of 0.22 kg (0.5 lb.) of TNT. Typically about 2-10 kg (5-25 lb.) of water is involved in recovery boiler explosions. The major factor determining the severity of the explosion is the amount of water coming into contact with the molten smelt. Currently there are no methods of preventing smelt-water explosions by modifying the chemistry of the process. The only known way of hindering the smelt-water explosion is to prevent smelt-water contact (Grace, 1992).

2.3 Normal Shutdown vs. Emergency Shutdown Procedure (ESP)

During regular shutdown the liquor guns stop spraying black liquor into the furnace. The air nozzles continue blowing air into the furnace until the char is completely burnt off. The smelt
is allowed to cool down until it solidifies. The operators examine the smelt by prodding it with long pipes to make sure that the molten smelt has in fact solidified everywhere before entering the furnace to wash away the bed with water.

Current operation of recovery boilers requires immediate shutdown if any water is suspected to have leaked from the tubes and entered the combustion chamber. Following are some of the general steps followed in an Emergency Shutdown Procedure (ESP) as recommended by BLRBAC (Adams et al., 1997):

- Activate alarms to clear personnel from recovery boiler area.
- Stop firing fuel (black liquor).
- Shut off the air supply while providing sufficient air above the char bed to purge gases from the furnace.
- Shut off the water feed to the boiler.
- Drain waterwalls to a level 8 feet above the low point of the furnace floor.
- Reduce the steam pressure as rapidly as possible, as soon as the boiler has been drained.

The boiler is drained and the water feed to the boiler is shut off to stop entry of water to the boiler. In order to prevent overheating of the water tubes, 8 feet of water is left in the waterwalls. Primary air ports are shut off to prevent combustion in the char bed. Some air flow is maintained to purge the furnace and prevent building up of combustible materials.

2.3.1 Char Bed Cooling

The cooling characteristics of char beds are of little interest during the normal operation of the boiler. It is only after an emergency shutdown procedure (ESP) that char bed cooling
becomes very important. An ESP can last from several hours to a few days with a cost accrued by the industry of up to $20,000 per hour ($1/2 million per day) in lost production (Grace, 1999).

An ESP can leave a residual bed consisting of char, molten smelt, and frozen smelt on the boiler floor. Char has a very low thermal conductivity and thus acts as an insulating layer on the molten smelt pool and around the "hot" pockets within the bed. The size of the char bed determines the amount of time it takes for the materials in the furnace to cool down to below the solidification temperature of smelt (about 720-740°C). Water washing can only begin after this temperature is attained everywhere.

The char can contain a large amount of heat depending on the size and porosity. Table 2-1 shows some estimation of the bed mass and heat content in a 10m x 10 m furnace based on the property values reported by ADL (Richardson and Merriam, 1977). The heat of oxidation of carbon is based on the heating value of 32.850 kJ/kg C. The potential heat release from oxidation of sulfide is based on complete oxidation of sulfate with a smelt sulfidity of 30% and a reduction efficiency of 90% (Kawaji et al., 1999).
As seen in Table 2-1 the heat of fusion of smelt is a small fraction of the sensible heat that has to be removed in order to cool the bed from 815°C to 540°C (Kawaji et al., 1999).

In order to determine the heat content of a bed it is necessary to determine the bed mass and the amount of fuel content that burns. Bed mass can be calculated if the volume and the porosity are known. Volume of the bed can be calculated but the porosity can not be easily measured. Heat released by combustion is primarily due to oxidation of carbon, which depends on the amount of carbon and availability of air. Sensible heat should be removed from all the solid materials so the temperature falls below the melting point of the smelt.

In cooling a char bed, heat is transferred internally within the bed to the boundaries and externally from the boundaries to the surroundings. Internal heat transfer is by conduction through the solid material. Internal heat transfer by convection is believed to be very small since gas flow is minimal within the bed. In some hot regions of the bed heat could be transferred by radiation across the pores.

| Table 2-1 | Mass and heat content of char bed in a 10m x 10m furnace (Kawaji et al., 1999) |
|-----------|--|--|--|
| **Bed Height, m** | **Bed 1** | **Bed 2** | **Bed 3** |
| **Porosity** | 50% | 50% | 75% |
| **Mass, metric tons (US tons)** | 212 (234) | 106 (117) | 53 (58) |
| **Sensible heat at 815°C (1500°F), GJ (MM Btu)** | 223 (211) | 112 (106) | 56 (53) |
| **Sensible heat at 540°C (1000°F), GJ (MM Btu)** | 145 (137) | 72 (68) | 36 (34) |
| **Sensible heat at 400°C (750°F), GJ (MM Btu)** | 105 (100) | 53 (50) | 26 (25) |
| **Heat of fusion (5% molten smelt), GJ (MM Btu)** | 1.5 (1.4) | 0.75 (0.7) | 0.38 (0.36) |
| **Heat of fusion (25% molten smelt), GJ (MM Btu)** | 7.5 (7.1) | 3.8 (3.6) | 1.9 (1.8) |
| **Heat of fusion (6 inch smelt pool), GJ (MM Btu)** | 4.1 (3.9) | 4.1 (3.9) | 4.1 (3.9) |
| **Heat of carbon oxidation (5% C), GJ (MM Btu)** | 347 (329) | 173 (164) | 87 (82) |
| **Heat of carbon oxidation (2% C), GJ (MM Btu)** | 139 (132) | 69 (65) | 35 (33) |
| **Heat of sulfide oxidation, GJ (MM Btu)** | 548 (519) | 274 (260) | 137 (130) |
External heat transfer is by natural or forced convection to the gases above the bed, radiation from the bed surface to the surrounding water walls and upper furnace, and conduction to the floor tubes and side walls. For practical purposes conduction to the side walls is ignored since the contact area is much smaller compared to that at the top and bottom (Grace, 1998).

Thermocouple measurements during char bed cool-down indicate a relatively constant rate of temperature decrease. Since the sensible heat in the bed is much larger than the heat of fusion of molten smelt, the rate of temperature decline is a direct measurement of the heat loss from the bed. Assuming that the bed is cooling from top and bottom, the average heat flux from the bed can be calculated using the following equation (Grace, 1998):

\[ Q_h = m_b C_{p,b} \left( \frac{dT}{dt} \right) / (2A_f) \]  \hspace{1cm} (2-1)

where \( Q_h \): average heat flux from the bed;
\( m_b \): mass of the material in bed;
\( C_{p,b} \): specific heat of material in bed;
\( \frac{dT}{dt} \): rate of temperature drop;
\( A_f \): cross sectional area of furnace.

Table 2-2 summarizes the average heat fluxes from the beds at several different cooling rates for the three beds discussed in Table 2-1. It is assumed that the heat of fusion of the molten smelt is negligible and there is no continued combustion (Grace, 1998).
Table 2-2  Heat fluxes associated with cooling rates (Grace, 1998)

<table>
<thead>
<tr>
<th>Cooling Rate/ Heat Flux</th>
<th>Bed 1</th>
<th>Bed 2</th>
<th>Bed 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W/m²</td>
<td>Btu/hr.ft²</td>
<td>W/m²</td>
</tr>
<tr>
<td>1.67°C/hr (3°F/hr)</td>
<td>655</td>
<td>208</td>
<td>338</td>
</tr>
<tr>
<td>3.33°C/hr (6°F/hr)</td>
<td>1310</td>
<td>416</td>
<td>655</td>
</tr>
<tr>
<td>5.56°C/hr (10°F/hr)</td>
<td>2183</td>
<td>693</td>
<td>1092</td>
</tr>
<tr>
<td>11.1°C/hr (20°F/hr)</td>
<td>4366</td>
<td>1386</td>
<td>2183</td>
</tr>
</tbody>
</table>

Without any bed disruption, the biggest resistance in cooling from the top surface of the bed is the internal resistance in heat flow from the bed interior to the surface. The thermal conductivity of the cold char or of a broken slag layer is about 0.087 W/mK (Richardson and Merriam, 1976 and 1977). For these conditions, a temperature gradient of 1820°C/m is required for a heat flux of only 160 W/m². This implies that most of the temperature gradient occurs over a distance of only about 10-15 cm (4 to 6 inches) at the bed surface, where the bed is coldest and radiation heat transfer within the pores is the lowest. Hence the internal temperature in cooling beds is expected to remain uniform except for regions where combustion occurs. For larger beds, heat loss from the top surface tends to be relatively lower than that to the floor but both directions are important (Grace, 1998).

The trapped molten smelt pockets in the char bed are considered a potential problem because of the long time required for such isolated pockets to cool and solidify. In a large bed it could take over 5 days for isolated smelt pockets to solidify (Richardson and Merriam, 1976 and 1977).

Operators use several methods to determine if the bed is ready for water washing. These include waiting for a given period of time, approximately 1 to 2 days, prodding the bed to see if there are any “hot” spots, and measuring the bed temperature. In some mills, the operators
attempt to accelerate the cooling of the bed by spraying a fine mist of water after a certain amount of time (Richardson and Merriam, 1977). These methods are all empirical with a lack of understanding of the heat transfer mechanisms behind them.

2.4 Accelerated char bed cooling

One way to shorten the bed cool-down time is to inject sodium bicarbonate or liquid carbon dioxide into the bed to disrupt the bed and accelerate the cooling process. It has been shown in some cases that a bed can be cooled in less than eight hours after initiating accelerated cooling (Kawaji et al., 1999). There is a study underway to examine the effectiveness of these coolants. Some critical unknowns in these investigations are as follows (Grace, 1999):

- Reliable values of the effective thermal conductivity of porous char beds
- Knowledge of conditions that result in trapped smelt pockets
- Ability to determine porosity and porosity distribution in the bed

2.5 Measurement of thermal properties of char bed materials

There is little information available about the properties of char and smelt in the recovery boilers. This is due to the fact that the temperature in the furnace is very high (as high as 900°C) and that molten smelt is extremely corrosive. These factors make it difficult to monitor simple properties such as specific heat, density, temperature distribution, and thermal conductivity of the char bed materials.
2.6 Arthur D. Little Inc. (ADL) Report

The ADL report is the only publication that has documented extensive experimental measurements on the properties of materials in recovery boilers. ADL’s work on recovery boilers can be divided into two main parts:

a) an experimental part which includes several mill visits and collection of field data.

b) a thermal modeling part in which ADL used a heat transfer model and the experimental data to predict:

i) thermal properties of the char and the smelt:

ii) cooling of the char bed.

2.6.1 Instrumentation Used

2.6.1.1 Temperature Measurement Probes

A five-junction thermocouple probe (Figure 2-5) was used to measure the temperature profile inside the char bed. It utilized five 0.04-inch diameter thermocouple wires enclosed in a 5/16-inch OD stainless steel tube with 0.035-inch wall thickness. The thermocouple junctions were spaced at 8-inch intervals so the temperature could be measured at five locations to a depth of 40 inches inside the bed. The output from each thermocouple was continuously monitored.

During the mill trials, it was observed that thermocouples with lower thermal mass were more versatile. This was because the materials with lower thermal mass had a smaller time constant; hence reached thermal equilibrium much faster. This allowed the thermocouples to read the temperatures soon after they were inserted into the bed. Thermocouples with long time constants failed due to corrosion.
Figure 2-5  A five-junction thermocouple probe (Richardson and Merriam, 1977)
2.6.1.2  Ball Heat-Flow Probe

A heat flow probe with a small spherical mass (Figure 2-6) was used to measure the thermal conductivity and thermal diffusivity of the char bed.

Figure 2-6  Schematic diagram of the ball-heat-flow probe used by the ADL (from Richardson and Merriam, 1977)
This technique used the time rate of temperature rise of a steel sphere to measure the thermal properties of the surrounding char. As shown in Figure 2-7, the temperature in the region near the ball would initially decrease as the bed loses heat to the initially "cold" ball. Meanwhile the temperature of the ball would increase as it gains heat from the surrounding bed. In a short while, the temperatures of both the ball and the surrounding bed would increase as heat flows from the farther parts of the bed to the ball and the regions near it.

![Diagram of temperature changes in bed and ball](image)

Figure 2-7  Theory of the ball-heat-flow probe (Richardson and Merriam, 1977)

ADL calculated the thermal diffusivity from the early part of the temperature rise of the ball and thermal conductivity from the latter portion of the temperature rise, when the temperatures of the ball and the surroundings approached each other. ADL explained that this was done because the initial part of the heating curve was strongly dependent on the thermal
diffusivity of the medium whereas the latter part of the heating curve was dependent more on the thermal conductivity.

A small thermocouple probe was placed at a known distance from the equator of the steel ball to measure the thermal diffusivity and thermal conductivity independently as a check. This small thermocouple, however, failed and hence the thermal diffusivity and the thermal conductivity measurements could never be cross-checked.

2.6.1.3 Bed Sampling Tubes

Core sampling tubes of 1-inch, 1.25-inch, and 2-inch OD and 2-foot length were used to remove samples from the char bed. Samples from different locations in the bed were collected.

2.6.2 Mill Visits

ADL researchers visited several mills with decanting-hearth (CE) and slanted-floor (B&W) type recovery boilers. The purpose of these visits was to gain a first hand experience in the operation of the recovery boilers, and to measure temperature and thermal properties in these beds.

ADL researchers explained that the significant difference in the thermal conductivity of the char from the Ticonderoga mill (CE boilers) and that from the Androscoggin mill (B&W boilers) was due to the difference in the type of boilers. They described that the CE boilers contained “inactive char” where no combustion could take place.

The B&W boilers, however, were considered to carry “active zones” where combustion and smelting would take place at high temperatures. ADL recommended a temperature dependent thermal conductivity, as opposed to a constant thermal conductivity, for the “active
zone" of the char accounting for heat transfer due to radiation in a porous material as given by Equation 2-2:

\[ k = 0.05 + 4 \phi D_p \sigma T^3 \]  

(2-2)

where

- \( k \): apparent thermal conductivity (BTU/hr.ft.°F);
- \( \phi \): porosity;
- \( D_p \): Pore diameter (ft);
- \( \sigma \): Stefan-Boltzman constant, \(0.1714 \times 10^{-8}\) (BTU/hr.ft\(^2\).°F);
- \( T \): Temperature (°R).

2.7 Effect of temperature on thermal conductivity of porous materials

There is experimental evidence that thermal conductivity of different porous materials in fact does vary with temperature (Litovsky et al., 1996). This variation, however, depends on the type and structure of the material under investigation. As Figure 2-8 indicates, the effective thermal conductivity of chrom-magnesite does not follow a certain pattern as the temperature increases.

![Figure 2-8](image)

Figure 2-8 Variations of thermal conductivity of poorly connected refractories with temperature for different gas pressures: (A) chrom-magnesite, \( \rho = 1.1\) g.cm\(^{-3}\) (N\(^2\) pressures of ((●) \(10^2\), (O) \(10^5\), and (□) \(5 \times 10^5\) Pa); and (B) yttrium oxide , \( \phi = 45\%\) (He pressures of (□) \(10^2\), (●) \(10^5\), and (O) \(10^5\) Pa). (Litovsky et al., 1996)
Other materials behave differently; for example the thermal conductivity of alumina always decreases as temperature increases (Figure 2-9A). On the other hand the thermal conductivity of fire clay always increases as the temperature increases (Figure 2-9B). Therefore thermal conductivity of char bed materials can follow either patterns.

![Figure 2-9 Variations of thermal conductivity of insulating refractories with temperature for different gas pressures: (A) alumina, ρ = 1.1 g.cm$^{-3}$ (N$^2$ pressures of (Δ) 10$^3$, (▲) 5 x 10$^2$, (O) 10$^2$, and (□) 10$^2$ Pa); and (B) fire clay, ρ = 0.6 g.cm$^{-3}$ (N$^2$ pressures of (Δ) 10$^5$, (▲) 2 x 10$^4$, (□) 10$^3$, and (O) 10$^2$ Pa). (Litovsky et al., 1996)]

2.8 Experimental evaluation of the effective thermal conductivities of packed beds at high temperatures

Nasr et al. (1994) investigated the effect of particle diameter and bed temperature on the rate of heat transfer due to both conduction and radiation in packed beds of spherical particles. Three different packing materials, alumina, aluminum, and glass, with various particle diameters (2.5 to 13 mm) were tested. Internal bed temperature profiles and the corresponding effective thermal conductivities were calculated for a temperature range of 350 K to 1300 K under steady state conditions. It was found that the effective thermal conductivity increases with particle size.
and with thermal conductivity of the packing material. Nasr et al. attempted to quantify the relative contributions of conduction and radiation.

Figure 2-10 shows the experimental apparatus used for the investigation. The apparatus was designed using guidelines from ASTM for measuring the thermal conductivity of refractories and insulation materials. The apparatus consisted of an electric furnace, a test cell, a cooling system, and a data acquisition unit.

![Diagram of the experimental apparatus](image)

Figure 2-10 Cross-sectional view of the conductive-radiative experimental apparatus (Nasr et al., 1994)

Thermocouples were placed at different vertical positions and the particles were randomly poured into the test cell. The test cell was raised into the furnace cavity and water flow through the flux calorimeter and the thermal guards were initiated. The heating elements and the data acquisition system were then activated. Steady state conditions were assumed to have reached when the temperatures inside the bed changed by no more than 1°C in a period of one hour. It took approximately seven to eight hours to establish steady state conditions.
For each run at a specific furnace temperature the heat flow through the packed bed was calculated using the water flow through the calorimeter and the inlet and outlet temperatures at steady state. The heat transfer rate was expressed as:

\[ Q_c = m_e C_p \Delta T_c \]  \hspace{1cm} (2-3)

where

- \( Q_c \): rate of heat removal by water flowing through the calorimeter;
- \( m_e \): mass flow rate of water through the calorimeter;
- \( C_p \): heat capacity of water;
- \( \Delta T_c \): difference between inlet and outlet water temperatures at steady state.

The effective thermal conductivity was computed from Equation 2-4.

\[ k_{\text{eff}} = \frac{-(Q_c/A_c)}{(dT/dx)} \]  \hspace{1cm} (2-4)

where

- \( k_{\text{eff}} \): effective thermal conductivity of the particle bed (includes both conduction and radiation effects);
- \( A_c \): cross sectional area of the calorimeter;
- \( dT/dx \): temperature gradient at any location in the bed.

Due to the lack of knowledge of the radiative property data (extinction coefficient, absorption coefficient, etc.), Nasr et al. (1994) simplified the radiative transfer in the bed using
the diffusion approximation. Assuming that natural convection effects are negligible and the steady state heat flow is one-dimensional, the heat diffusion equation becomes.

\[ \frac{dq}{dx} = d \left( -k_{\text{cond}} \frac{dT}{dx} + q_r \right) / dx = 0 \]  \hspace{1cm} (2-5a)

\[ = d \left( -k_{\text{eff}} \frac{dT}{dx} \right) / dx = 0 \]  \hspace{1cm} (2-5b)

where \( k_{\text{eff}} (T) = k_{\text{cond}} (T) + k_r (T) \). Many expressions for \( k_r \) have been developed but in general they may be represented by a generic expression of the Damköhler type for the radiative conductivity as follows:

\[ k_r = 4 E \, d_p \, \sigma \, T^3 \]  \hspace{1cm} (2-6)

The exchange factor \( E \) is a model-dependent parameter and is usually a function of the particle emissivity and possibly the particle shape and bed porosity.

The contribution to heat transfer by conduction and radiation was represented by the following equation.

\[ k_{\text{eff}} = 0.8 \, k_{\text{cond, Z-B-S}} + 4 \varepsilon \, d_p \, \sigma \, T^3 \]  \hspace{1cm} (2-7)

where \( k_{\text{cond, Z-B-S}} \) is the effective thermal conductivity obtained from Zehner-Bauer-Schlunder model.
3.1 Apparatus

The measurements of the effective thermal conductivity of char bed samples were performed using an apparatus constructed with a design similar to that recommended for measuring the thermal conductivity of carbon refractories (ASTM, 1999). The apparatus was constructed to provide a one-dimensional heat transfer through the sample. It allowed for accurate measurements of the bed temperature profile using thermocouples, and the heat removal rate from which the effective thermal conductivity was calculated. The major components of the experimental apparatus consisted of a heating unit, a cooling unit, a test chamber, and a data acquisition unit (Figure 3-1). Following is the description and function of each unit.

![Diagram of the experimental apparatus]

Figure 3-1  a) Schematic diagram of the experimental apparatus
3.1.1 Cover

The cover was constructed of insulating firebricks to prevent upward heat loss. Also the heating plate was mounted under the cover. The cover could be completely lifted off the rest of the apparatus to allow for loading of the bed sample and cleaning of the test chamber.

3.1.2 Heating Unit

The heating unit consisted of a ceramic heating plate (15.5 x 15.5 cm), height adjusting wires, a thermocouple, and a temperature control unit. The heating plate was attached to the cover by the adjusting wires. The wires allowed for adjusting the height of the heating plate inside the test chamber so that the heating plate could rest just on top of the char sample. A
thermocouple was placed through the top cover in the center of the heating plate to monitor the surface temperature of the heating plate. A temperature control unit regulated operating temperature of the heating plate to a prescribed temperature set point.

3.1.3 Test Chamber

The test chamber was a cavity in the middle of the apparatus in the shape of a square based column (16 x 16 x 20 cm). It was surrounded by firebrick insulation as shown in Figure 3-2 to minimize heat flow in the radial direction.

![Figure 3-2](image)

Figure 3-2  Top view of the test chamber (16 cm x 16 cm x 20 cm)

3.1.4 Cooling Unit

This unit included a cooling plate, two water inlets and two water outlets, thermocouples to measure water temperatures at the inlets and outlets, and a flowmeter. The cooling plate was
made of two square steel plates (15.5 x 15.5 cm). Two water channels were carved in the bottom steel plate, Figure 3-3. A sheet of Teflon with a thickness of approximately 5 mm was used in between the two steel plates to seal water in the channels. The two corresponding water channels ensured that the temperature in the cooling plate would be uniform. If only one channel was used then the water inlet side would be colder than the water outlet side. Thermocouples were used at the water inlet and outlet to monitor the corresponding temperatures. A flowmeter was installed at the water inlet to measure the flowrate.

![Cooling plate. a) top view of the bottom plate (15.5 cm x 15.5 cm). b) side view](image)

3.1.5 Insulating Walls

Special attention was paid to the materials used for the walls. It was important to use materials with thermal conductivity significantly lower than that of the char samples in order to
induce a one-dimensional heat flow. It was also essential to fabricate the walls from a material that would withstand the high operating temperatures. Insulating firebricks were used on the inner side of the walls because they can endure the high temperatures and do not react with the char materials. On the outer side of the walls a layer of porous silica with a thermal conductivity much lower than that of firebricks was used to further prevent radial heat loss from the side walls. The thermal conductivity of this material was reported to be 0.028 W/m°C (0.195 Btu.in/hr.ft².°C) at 260 °C.

Despite the low thermal conductivity of the insulating materials, there was horizontal heat loss from the apparatus simply because the insulation was not perfect. However, this heat loss was small and did not significantly affect the final results. As shown in Appendix A the maximum heat loss from the horizontal walls was less than 6% of the total heat flow through the char samples.

3.1.6 Steel Case

The entire structure of the apparatus was enclosed in a steel square case (44 x 44 x 28 cm) to protect the individual components.

3.1.7 Thermocouples

A total of 15 thermocouple holes, each 2 cm apart, were drilled through two opposite sides of the steel case and the insulating walls. The first hole from the bottom was drilled so that the thermocouple at that location was on top of the cooling plate. The first hole on the opposite side was 1 cm above the cooling plate, and so on. Only a certain number of thermocouples were
used to monitor the temperature profile in each run depending on the amount of char sample. Thermocouple holes not in use were plugged with a mud sealant.

As mentioned earlier, thermocouples were installed in the water inlets and outlets of the cooling plate to monitor the corresponding water temperatures. Also, thermocouples were mounted on the surface of the steel case to examine the surface temperature of the insulating walls.

### 3.1.8 Data Acquisition

A PC-based data acquisition system with 12 thermocouple channels was used to monitor and record the temperature profile inside the char sample, the inlet and outlet water temperatures circulating in the cooling plate, and the surface temperature of the walls. Temperatures were monitored every 4 seconds and recorded every 5 minutes.

### 3.2 Calibration

Firebricks with known thermal conductivity were tested in the experimental apparatus to test the accuracy of the apparatus and the procedure. Firebricks (23 x 11 x 6 cm) were cut to fit the test chamber. Holes, 7.5 cm long and 0.16 cm (1/16") in diameter were drilled horizontally through the firebricks at specific locations. Thermocouples were inserted into the holes inside the bricks to monitor temperatures. Thermocouples were pressed against the firebrick to ensure good contact. The following procedure was followed to experimentally determine the thermal conductivity. These were compared with the reported data to verify the accuracy of the experimental apparatus.
3.3 Char Samples

Char samples tested were obtained from the following three sources:

3.3.1 Samples From Mill A

Char bed materials were obtained from the smelt spout of an operating recovery boiler. During the test, the boiler was operating with a low bed and therefore it was difficult to obtain char bed materials without collecting some molten smelt as it flowed through the spout. Also, the draft of air into the spout made it difficult for the operators to collect flaky char materials. In all the char samples collected, there was frozen smelt present at the bottom once the sample was allowed to cool. The color of the samples was grayish (Figure 3-4). Four different runs were conducted using char from this boiler:

3.3.1.1 Mill A-1 Char sample was directly placed from the recovery boiler into the test chamber. Thermal conductivity measurements were performed onsite.

3.3.1.2 Mill A-2 Char sample was allowed to cool down once it was collected from the boiler, then it was placed in the test chamber. Thermal conductivity measurements were performed onsite.

3.3.1.3 Mill A-3 Char sample was taken to the laboratory where thermal conductivity measurements were done.

3.3.1.4 Mill A-4 Char sample labeled Mill A-3 was crushed to a powder with a grinder to reduce porosity. This sample was then used to measure thermal conductivity in the laboratory.
a) Mill A sample being collected from the smelt spout

b) Mill A sample immediately collected from the boiler

c) Mill A-3

Figure 3-4  Mill A samples
3.3.2 Laboratory made samples

Char samples were also made in the lab using black liquor from an operating plant. Black liquor at room temperature was heated in a water bath for about 1-2 hours at 70-80°C to reduce viscosity. Heated black liquor was then mixed well and poured into a metal crucible inside a furnace. The crucible was then placed inside a pyrolysis chamber. The chamber was sealed and nitrogen gas at relatively low flow rate, approximately 5 cm³/min, was passed through the chamber to prevent the combustion of char. The sample was heated for about 10 minutes at 600°C to dry the black liquor and vaporize all the water. The temperature was then increased from 600 to 700°C, and the sample was kept at this temperature for 50 minutes to complete the pyrolysis of black liquor. After this stage, the furnace was turned off while nitrogen gas was circulated through the sample until the charred black liquor was cooled to about 80-100°C. About 300-400 g of black liquor produced about 150-170 g of char. Two runs were conducted to obtained the following samples:

3.3.2.1 Lab-1 Char made in the lab had a quite different appearance and structure than that of char obtained from recovery boilers. It was in the shape of a cylinder and had to be broken up in order to fit into the apparatus. Some fragments of the sample were hollow cylinders while other fragments were cylinders with a flaky structure inside. This laboratory-made sample was much harder to break and appeared black (Figure 3-5).

3.3.2.2 Lab-2 Char sample labeled Lab-1 was crushed to a powder with a grinder and tested for thermal conductivity.
A simulated ESP experiment was conducted at Mill B Industries plant. After the ESP started, a sample of char bed materials was collected by an operator through a primary air port. Due to the small size of the port, approximately 12 x 15 cm, only a small amount of char could be collected. Unlike the Mill A samples, very little molten smelt was scooped out while
collecting the char materials because the sample was taken from the top of the bed. The char material was covered and allowed to cool down before it was taken to the laboratory for testing.

3.3.3.1 Mill B-1: The sample was very much like the Mill A samples in structure. The sample was black and there was much less frozen smelt at the bottom than the Mill A samples (Figure 3-6).

![Burning Char](image)

Figure 3-6 Mill B sample

3.4 Density Measurement

The total weight of each sample was measured before it was placed into the test chamber. The height of the sample inside the test chamber was also measured. The density of the sample was calculated from this information as mass per unit volume.
3.5 Porosity Measurement

Porosity is defined as the percentage of total void volume in a total sample volume. This property was determined as follows:

a) A sample was placed inside a beaker. The volume of this sample, \( V_s \), was calculated by measuring the dimensions of the beaker.

b) the sample was crushed into a fine powder with a grinder.

c) the powder was mixed with a known volume of vegetable oil, \( V_o \), and was allowed to sit for about fifteen minutes to ensure all air bubbles were released.

d) the volume of the vegetable oil-powder mixture, \( V_f \), was determined,


e) material volume, \( V_m \), was determined by subtracting the initial volume of oil from the final volume of oil and sample. \( (V_f - V_o) \).

f) total void volume, \( V_a \), was found by subtracting the material volume from the total volume. \( V_a = V_s - V_m \).

g) porosity was calculated by finding the percent void volume in total volume using equation 3-1.

\[
\text{Porosity} = \frac{V_a}{V_s} \times 100\% \quad (3-1)
\]

Although it is very difficult to measure the exact volume of voids in a porous material, the above procedure was developed to determine the porosity of the char bed samples as accurately as possible. The sample was crushed to break the structure and get rid of as much void volume as possible. The powder was added to a liquid so that the liquid material would fill the spaces between the solid particles and replace the void. Since char materials are soluble in water, a vegetable oil was used to prevent dissolution of the sample in the liquid.
3.6 Experimental Procedure

After positioning thermocouples and measuring their vertical locations in the test chamber, the char particles were randomly poured into the test chamber and the surface was leveled. The top cover, to which the heating plate was attached, was then lowered so that the heating plate would just sit on top of the char sample. The heating plate was turned on and the temperature control was set to a specific temperature. The temperature control kept the heating plate at the specific set point throughout the run. Water flow through the cooling plate was then initiated. The data acquisition system was activated to monitor and record the temperature profile inside the sample, inlet and outlet water temperatures, and the surface temperature of the experimental apparatus.

Typically about five to six hours were required to establish a steady state condition. The steady state condition was assumed to have been reached when the temperatures inside the sample as well as the water temperatures and the vessel wall temperatures no longer changed by more than 3°C during a one-hour period. After recording the steady state water flow rate and all the temperatures, the heating plate set point temperature was changed to initiate another run. After completing runs at several heating plate temperature set points, the char sample was allowed to cool down. The particles were removed from the test chamber, and the test chamber was cleaned using a vacuum cleaner. The entire procedure was repeated for other char samples.

3.7 Data Processing

As mentioned earlier, there were a total of seven samples investigated in this project. For each of these samples, a number of runs at various heating plate temperature-set-points were
conducted. To ensure that steady state had been indeed reached, the temperature history inside the sample was plotted for each run. For example, Figure 3-7 shows such a plot for Lab-1 sample at a heating plate set point of 250°C. A constant temperature history after 4 hours confirmed that steady state had been reached.

![Temperature history of Lab-1 sample at set point of 250°C](image)

Figure 3-7 Temperature history of Lab-1 sample at set point of 250°C

Similar temperature histories were plotted for wall surface temperatures, and inlet and outlet water temperatures to make sure steady state had been reached.
The steady state temperatures were then used to calculate the effective thermal conductivity as follows:

a) Heat removed by the circulating water was determined using equation 3-2.

\[ Q_c = m_w C_{p,w} (T_{in,w} - T_{out,w}) \]  

(3-2)

where

- \( Q_c \): Rate of heat removed by the water at steady state (W)
- \( m_w \): Mass flow rate of water at steady state (g/s)
- \( C_{p,w} \): Heat capacity of water (J/g.\(^\circ\)C)
- \( T_{in,w} \): Water inlet temperature at steady state (\(^\circ\)C)
- \( T_{out,w} \): Water outlet temperature at steady state (\(^\circ\)C)

b) Assuming a constant temperature gradient between any two thermocouple locations in the sample, Equation 2-4 was simplified to equation (3-3)

\[ k_{eff} = -(Q_c/A_c) / (\Delta T/\Delta x) \]  

(3-3)

where

- \( k_{eff} \): effective thermal conductivity of the sample (W/m.K)
- \( A_c \): cross sectional area of the calorimeter (m\(^2\));
- \( \Delta T \): steady state temperature difference between two consecutive thermocouples (\(^\circ\)C)
- \( \Delta x \): vertical distance between two consecutive thermocouples (m)
The effective thermal conductivity calculated was assumed to be that of the char bed materials at the average temperature, $T_{avg}$. Between the two consecutive thermocouples. Other steady state temperatures were used to determine $k_{eff}$ at other values of $T_{avg}$. The above procedure was repeated in all the runs for each sample. A graph of effective thermal conductivity versus $T_{avg}$ was produced for each sample. The error associated with this calculation was determined, see Appendix C.

3.8 Numerical Simulation

As explained earlier, in order to calculate the thermal conductivity using the experimental apparatus, it was assumed that heat transfer through the sample from the heating plate to the cooling plate was completely one-dimensional. Therefore it was assumed that no heat traveled through the thick insulation walls surrounding the sample. In order to verify this assumption, a computational fluid dynamics (CFD) code, PHOENICS, was used to develop a computer model that could simulate the heating of samples tested in the experimental apparatus.

3.8.1 Description of the simulation model

The PHOENICS code was used to model the entire experimental apparatus in a 3-dimensional heat transfer model. Char thermal conductivity determined experimentally was used in the model and the steady temperature distribution inside the sample was predicted. By comparing the temperature distributions obtained experimentally with those predicted by the simulation, the validity of the assumption was determined as discussed in the following section. Necessary corrections were made to account for the 3-dimensionality of heat flow.
3.8.2 **Geometry of the computational domain**

Figure 3-8 shows the computational domain of the heat transfer model. All the components of the apparatus and the sample were modeled as a different material with the appropriate dimensions and properties.

In the model, the entire apparatus was surrounded by air. Also, appropriate sized blocks of air represented the gap between the cover and the heating plate and the gap between the cooling plate and the bottom insulation bricks as shown in Figure 3-8. The two wall materials, the inner insulation bricks and the outer micro-porous silica insulation, were modeled as blocks with constant thermal conductivity values. Since the simulation was performed under steady state conditions, thermal conductivity was the only value that had to be specified for these materials. The thermal conductivity of the material was reported by the brick supplier to be constant for the temperature range of interest. Therefore, constant thermal conductivity values of 0.16 W/m°C and 0.02 W/m°C were specified for the blocks representing the insulation brick and micro-porous insulation blocks, respectively. The heating plate was modeled as a slab with a constant temperature. The temperature of the hot slab, in °C, was the only variable that had to be specified. The cooling plate was represented by a heat sink. The constant value of heat removal rate in W had to be specified for the heat sink. The vertical temperature profile within the sample was recorded by a temperature monitor in the center of sample. The PHOENICS q1 files, which include the properties, dimensions, and locations of each constituent component are included in Appendix B.
3.8.3 Heat transfer equations

PHOENICS provided a solution to the 3-dimensional heat conduction equation in Cartesian coordinates described by equation 3-4.

\[ q = k \left[ \frac{dT}{dx} + \frac{dT}{dy} + \frac{dT}{dz} \right] \tag{3-4} \]

where \( q \) is the rate of heat transfer in W, and \( k \) is the thermal conductivity in W/m\(^\circ\)C, which may be a function of temperature. The heat transfer rate was specified as the heat removed by the heat sink. Thermal conductivity of each material was specified separately.
3.8.4 **Boundary and initial conditions**

For all simulations, the natural convection heat transfer coefficient for the surrounding air was specified to be 3.3 W/m²°C. This value was determined using the method described in Appendix A. The initial temperature of the surrounding air and all the components of the model was set to be 25°C.

3.8.5 **Simulations**

The above model was used to run various simulations. Firebrick and char bed properties were used to specify the thermal conductivity of the sample. All the firebrick experiments and one Mill A-3 experiment were simulate using the above model. Table 3-1 summarizes the properties used in each simulation.

<table>
<thead>
<tr>
<th>Sample used in experiment</th>
<th>Thermal Conductivity of Sample (W/m°C) set in simulation</th>
<th>Hot slab Temp. (°C)</th>
<th>Heat Sink Rate (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firebrick, 600</td>
<td>0.44</td>
<td>620</td>
<td>62.1</td>
</tr>
<tr>
<td>Firebrick, 700</td>
<td>0.45</td>
<td>710</td>
<td>68.3</td>
</tr>
<tr>
<td>Firebrick, 800</td>
<td>0.45</td>
<td>815</td>
<td>79.4</td>
</tr>
<tr>
<td>Firebrick, 900</td>
<td>0.55</td>
<td>920</td>
<td>101</td>
</tr>
<tr>
<td>Mill A-3, 500</td>
<td>0.18</td>
<td>550</td>
<td>31.4</td>
</tr>
</tbody>
</table>

The first column in Table 3-1 shows the material tested in the experimental apparatus. The number next to the material indicates the temperature of the heating plate for the specific experimental run. The second column gives the thermal conductivity value that had to be used in each simulation in order to duplicate the experimental steady temperature profile. The hot slab
temperature is the temperature prescribed to the heating plate. The heat sink rate is the heat removal rate specified for the heat sink. This value was the same as the heat removal rate of the cooling plate for the corresponding experimental run.

As described earlier, each simulation provided the steady temperature profile in the vertical direction. Therefore, in order to simulate a certain experiment, the above model was used with the following adjustments:

a) The heat sink rate was set to be equal to the amount of heat removed by the cooling plate at steady state for that particular experimental run. For example, for the calibration experiment where thermal conductivity of firebrick was determined and the heating plate temperature was set to 600°C, the heat removed by the cooling plate was 62.1 W. Therefore the heat sink removal rate in the simulation was set to 62.1 W.

b) The temperature of the hot slab, representing the heating plate in the simulation, was set so that the temperature at the location of the highest thermocouple was the same for both simulation and experiment. For example, for the experimental run, firebrick-600, the steady temperature recorded by the highest thermocouple, located at a height of 10.3 cm, was 471°C. The hot slab temperature for this situation was changed until the temperature predicted by the simulation at 10.3 cm was 471°C. This was necessary as the contact resistant at the plate-sample interface was unknown.

c) Thermal conductivity of the sample was then varied to change the slope of the steady temperature profile. The final thermal conductivity according to simulation
was selected when the slope of the steady temperature profiles for both experimental and simulation was the same.

d) The thermal conductivity that provided the same steady temperature profile as the experimental temperature profile was selected as the thermal conductivity of the sample when 3-dimensional heat transfer was considered.
4.1 Calibration of the measurement system

As described in the previous chapter, insulation firebricks with known thermal conductivity values were used to test the accuracy of the experimental method and data analysis procedure. Figure 4-1 shows a comparison between the measured thermal conductivity and the value recommended by the supplier of this particular firebrick.

![Figure 4-1 Calibration results](image-url)
In this figure, the bottom region refers to the thermal conductivity, \( k \), values measured using the thermocouples located within 2 cm of the bottom of the sample. Similarly, the top region represents the \( k \) values found using the thermocouples within 2 cm of the top of the sample. The middle region denotes the \( k \) values determined using the thermocouples between the top and the bottom regions.

The results indicate that there is good agreement between the measurements made in the middle region and the recommended values. The \( k \) values found in the top and bottom regions, however, overestimated the reported thermal conductivity. The high thermal conductivity measured in the top region was due to the fact that the temperature gradient between the highest thermocouple and the one immediately below was lower than expected. This could be due to three-dimensional heat transfer in the top region which was close to the hot heating plate. Therefore assuming one-dimensional heat transfer in the top region of the sample, i.e. within 2 cm to the top surface, may not yield an accurate measurement of thermal conductivity.

For the bottom region, the higher than recommended thermal conductivity was again due to the low temperature gradient between the lowest thermocouple and the one immediately above it. It was believed that the contact resistance between the cooling plate and the sample could affect this temperature gradient, however this behavior was not fully understood.

Based on the predicted and reported values of thermal conductivity, it was concluded that:

- Thermal conductivity determined using the temperature gradients measured by thermocouples located well inside the sample was fairly accurate.
Thermal conductivity values determined from the thermocouples located within 2 cm of the top and bottom surfaces of the sample were overestimated. Non-linear temperature variations in these regions are likely due to the 3-dimensional effects and contact resistance.

4.2 Porosity and Density

Porosity of each sample was calculated before the sample was tested in the thermal conductivity apparatus using the method described in Chapter 3. The density of the sample was determined each time the heater temperature was changed by measuring the reduction in the sample height. Table 4-1 summarizes the density and porosity values for each sample. Density of the material obtained from Mill A without any pores was estimated to be approximately 1.78 (g/cm³). The values of the char samples made in the lab and also the samples obtained from Mill-B boiler were both 2.8 (g/cm³), indicating that these two samples were similar in composition.
Table 4-1  Summary of density and porosity of char samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Porosity %</th>
<th>Set Point (°C)</th>
<th>Density (g/ cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>200</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>300</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>400</td>
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<tr>
<td></td>
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<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>700</td>
<td></td>
</tr>
<tr>
<td>Mill A-3</td>
<td>65</td>
<td>250</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td></td>
<td>400</td>
<td></td>
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</tr>
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<td></td>
<td></td>
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<td></td>
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<td>800</td>
<td></td>
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<tr>
<td>Mill A-4</td>
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<td>250</td>
<td>0.90</td>
</tr>
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</tr>
<tr>
<td></td>
<td></td>
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</tr>
<tr>
<td>Lab-1</td>
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<td>250</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td>750</td>
<td>0.26</td>
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<td>Lab-2</td>
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<td></td>
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<tr>
<td></td>
<td></td>
<td>650</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>750</td>
<td>0.91</td>
</tr>
<tr>
<td>Willamett</td>
<td>80</td>
<td>250</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td></td>
<td>500</td>
<td></td>
</tr>
</tbody>
</table>

4.3  Laboratory Samples

4.3.1  Lab-1

As described in Chapter 3, the char samples made in the lab had a different structure than those obtained from recovery boilers. The samples were made in a cylindrical vessel and therefore took the shape of the vessel. They were in the form of an almost hollow cylinder with a large void in the center, resembling a pipe.
The pipe-shaped sample had to be broken in order to fit the test chamber of the thermal conductivity apparatus. This resulted in the half-pipe shaped chunks of the char sitting on top of one another in the thermal conductivity apparatus. The structure and color of the sample did not change significantly at the end of the experiment.

The measured effective thermal conductivity of the porous laboratory sample, Lab-1, was found to be very low, 0.12 W/m°C at 100°C, then increase sharply with temperature as shown in Figure 4-2. This figure indicates that the temperature-dependent thermal conductivity model, equation 2-2, suggested by Richardson and Merriam (1977) and indicated by a solid line can describe the experimental data relatively accurately, if the porosity and pore diameter are properly selected.
The porosity of the Lab-1 sample was measured to be 92%. It was not possible, however, to measure the pore diameter because the pore sizes varied from microscopic ones to those that were about 4 cm in diameter. A value of 7.5 mm was used in the above equation to fit the experimental values. The pore diameters for this sample ranged from about 0.2 mm to about 40 mm. Several pore diameters were used in the Richardson and Merriam’s model but 7.5 mm fit the experimental data accurately.

4.3.2 Lab-2

The laboratory sample, Lab-2, was obtained by crushing the porous laboratory sample into a fine powder. The effective thermal conductivity was measured at various temperatures, as shown in Figure 4-3. The figure shows that thermal conductivity did not vary with temperature as strongly as it did for the Lab-1 sample. Thermal conductivity remained relatively constant below about 400-500°C and then increased slightly at 650°C.

![Image of a graph showing effective thermal conductivity variation with temperature for Lab-2 sample](image)

Figure 4-3  Effective thermal conductivity variation with temperature for Lab-2 sample
The Richardson and Merriam's temperature-dependent model (4-1) failed to predict these results. When a porosity of 70% and a pore diameter of 2.5 mm were arbitrarily used, the model shown by a solid curve fit the points only at higher temperatures. In the modified Richardson and Merriam's temperature-dependent model shown by a dashed curve, a solid thermal conductivity of 0.20 W/m°C was used instead of the recommended 0.087 W/m°C, while porosity and pore diameter were unchanged. Now the modified model fit the data at low temperatures below 300°C, but overestimates the data at higher temperatures. Thus, it can be concluded that Richardson and Merriam's model predicts a different temperature dependence from that of the experimental data and therefore cannot be used in this case to correlate the thermal conductivity data.

In comparing the thermal conductivity variations between the porous Lab-1 and crushed Lab-2 samples (Figure 4–4), it was observed that a change took place in the structure of the less porous sample at higher temperatures, and this completely changed the thermal conductivity variation with temperature.

![Effective Thermal Conductivity vs Temperature](image)

**Figure 4–4** Effect of structure and porosity on the thermal conductivity behavior for laboratory-made samples
The more dense crushed sample, Lab-2, had a higher thermal conductivity value of about 0.25 W/m°C at low temperatures below 200°C, while the value for the less dense Lab-1 sample was about 0.15 W/m°C. This is because the Lab-2 sample was more closely packed and hence the solid thermal conductivity should be higher in the absence of any radiation effect.

Since the Richardson and Merriam's temperature-dependent model could predict the thermal conductivity of the porous laboratory sample, Lab-1, and the structure of the sample did not seem to change during the experiment, the increase in the thermal conductivity with temperature is believed to be entirely due to radiation through the pores. As mentioned before, the Richardson and Merriam's model attributes all changes in the thermal conductivity at high temperatures to radiation. Although the porosity of the Lab-2 sample after crushing was still quite high, about 70%, a change in the structure of the material is believed to have changed the mechanism of heat transfer.

4.4 Mill Samples

4.4.1 Mill A-1 and Mill A-2

Thermal conductivity measurements for the two mill samples were conducted onsite at a pulp and paper mill. Due to time constraint, only one run could be performed for each sample. The results obtained from these tests were in agreement with the results for the Mill A-3 sample, which was obtained from the same mill.

4.4.2 Mill A-3

This sample was obtained from the furnace of an operating recovery boiler. The effective thermal conductivity for this sample, Mill A-3, was found to remain more or less constant below
about 500°C. Figure 4-5. It then increased sharply with temperature. The trend observed was different from that predicted by the Richardson and Merriam's model. Hence it was concluded that the increase in the effective thermal conductivity was not solely due to radiation. Since the increase in thermal conductivity began only at temperatures higher than 500°C, which is close to the first melting point of smelt, this increase is thought to be due to the change in the structure of the char sample. Other factors affecting this increase could be the increased solid thermal conductivity at high temperatures, and also radiation heat transfer through the pores.

![Graph showing the variation of effective thermal conductivity with temperature for Mill A-3.](image)

**Figure 4-5** Variation of effective thermal conductivity with temperature for Mill A-3
4.4.3 Mill A-4

This sample was obtained by crushing the above sample into a powder. Effective thermal conductivity remained relatively constant for temperatures below 500°C and increased sharply with temperature beyond 500°C, Figure 4-6. This behavior is very similar to that of porous version, Mill A-3. Thus, the change in the structure of the sample did not seem to affect the heat transfer mechanisms through the sample significantly.

![Graph showing effective thermal conductivity variation with temperature for Mill A-4](image)

**Figure 4-6**  Variation of effective thermal conductivity with temperature for Mill A-4

4.4.4 Mill B

As described before, the Mill B sample was collected from the top of a char bed following an emergency shutdown procedure. Since the sample had to be obtained through an air port, only a small amount of sample would be collected. The thermal conductivity variation is shown in
Figure 4-7. Since the cooling plate temperature was about 10-60°C, when there was only a small amount of sample present, it was not possible to create temperature gradients higher than about 500°C for this sample. Therefore, it was not possible to measure thermal conductivity at temperatures higher than about 550°C.

The effective thermal conductivity data for all the char samples obtained from different recovery boilers and having different porosity and pore size are shown in Figure 4-8. In all cases the thermal conductivity remained constant at temperatures below 500°C and increased sharply with temperature above 500°C. The thermal conductivity of the Mill B-80% sample was lower than those of the other two samples. This is thought to be due to higher density of pores which act as
insulation throughout the sample. Similarly the sample Mill A-55% had a higher thermal conductivity than the other two mill samples at temperatures below 500°C. The thermal conductivity of Mill A-65% was in between that for Mill A-55% and Mill B-80%. As mentioned earlier, the two samples obtained from mill A were different in structure, since one was used immediately after removed from the boiler, and the other was crushed to a powder. This difference in structure, however, did not affect the thermal conductivity behavior as evident in Figure 4-8.

![Figure 4-8](image)

Figure 4-8  Effective thermal conductivity of char bed materials measured assuming no heat transfer through the insulation walls.
Fluffy, dust-like fume deposits may become hard and resistant to sootblowing through sintering, a process that can occur at temperatures below the melting point of the material. During sintering particles become bonded together. First, a grain boundary forms at the location where the particles touch. Then, as particles are heated, the difference in free energy between the grain boundary and the particle surfaces causes the material to diffuse as shown in Figure 4-9 (Tran, 1997).

![Figure 4-9 Schematic of the sintering process (Tran, 1997)](image)

The rate of sintering is controlled by the rate of material diffusion and is strongly dependent on the particle size and temperature. Sintering occurs rapidly at high temperatures. This rate can also be accelerated by a small amount of liquid phase to facilitate the diffusion of material at the bridge area. In recovery boilers, sintering occurs due to high temperatures. Tran (1997) suggested that sintering in most of recovery boilers start at about 300°C, with a more shrinkage
of material occurring at higher temperatures. Figure 4-10 shows the SEM photographs of cross-sections of pellets sintered in 1 hour.

![SEM photographs of cross-sections of pellets sintered for 1 hour](image)

Figure 4-10  SEM photographs of cross-sections of pellets sintered for 1 hour (Tran. 1997)

Anderson et al. (1987) and Robinson et al. (2000) both suggest that sintering can cause a substantial increase in the effective thermal conductivity of the recovery boiler deposits. For the char materials that reached temperatures above 500°C, the particles fused and formed a hard crust as evident in Figure 4-11. Therefore, it can be concluded that sintering in the char bed materials and melting of the smelt content of char play an important role in increasing the effective thermal conductivity of char bed materials as temperature increases. Also, the increase due to sintering in effective thermal conductivity was quantitatively found by measuring $k_{eff}$ after
the sample was heated up to about 550°C. At this temperature, some sintering was expected to have occurred. Due to lack of enough samples however, only a few data points were obtained. Figure 4-12 shows that the thermal conductivity at about 250°C increases from 0.3 W/m°C before sintering to about 0.6 W/m°C after sintering was believed to have occurred. It is further concluded that radiation through pores is not the sole factor in the increased thermal conductivity of char bed materials as suggested by Richardson and Merriam (1977). Radiation may partially contribute to the increase in effective thermal conductivity.

Figure 4-11  Hard crust formed when sample was heated beyond 500°C. Mill A-4
The temperature-dependent thermal conductivity model recommended by Richardson and Merriam (1977) failed to predict the present thermal conductivity data for char bed materials obtained from recovery boilers. Furthermore, it is difficult to use their temperature-dependent thermal conductivity model because the porosity and pore diameter of char are difficult to determine. Moreover, it seems that the effective thermal conductivity of char bed materials increases due not only to radiation at high temperatures, but also sintering which according to Tran (1997) starts at about 450°C. Another minor factor, which may add to the increase, is the change in the solid thermal conductivity as the temperature varies. This could be an increase or a decrease in thermal conductivity depending on the properties of the material (Incropera and DeWitt. 1996).
4.5 Numerical Simulation Results

As described earlier in Chapter 3, in order to calculate the thermal conductivity it was assumed that heat transfer through the sample, from the heating plate to the cooling plate, was completely one-dimensional. Therefore it was assumed that no heat traveled through the thick insulation walls. In order to verify this assumption, a computational fluid dynamics (CFD) code, PHOENICS, was used to develop a computer model that could simulate the heating of samples tested in the experimental apparatus.

Four different simulations were conducted to predict the heating of firebricks that were used in the calibration section. Figure 4-13 shows the comparison between the temperature profiles obtained from simulation and the experiment.

![Figure 4-13](image)

Figure 4-13 Steady temperature profile inside firebrick for heating plate temperature of 600°C
As Figure 4-13 indicates, when a constant thermal conductivity of 0.44 W/m°C was assigned to the block representing the firebrick sample in the simulation model, PHOENICS could predict the experimental temperature profile well within the sample accurately. For the experimental temperature readings close to the top and the bottom surface, PHOENICS failed to predict the steady temperature. A much larger $k$ value of 1.2 W/m°C had to be used to fit the top experimental readings. Similarly, the bottom temperature was higher than that predicted by the simulation. Thus, as in the calibration results shown in Figure 4-1, the temperature readings from areas within 2 cm of the top and bottom surfaces may not yield an accurate measurement of thermal conductivity. The reason for this behavior was not fully understood.

The thermal conductivity for the firebrick at 300°C was found experimentally to be about 0.52 W/m°C. Using the simulation, however, this value was found to be 0.44 W/m°C resulting in a difference of about 15%. This was believed to be due to heat loss from the apparatus and also heat transferred through the thick insulating walls.

A simulation was also conducted using properties of char bed materials for Mill A-3. Similar behavior as for the firebrick sample was observed. Thermal conductivity according to simulation was found to be 0.18 W/m°C, but experimentally, it was determined to be about 0.21 W/m°C, a difference of 14% from the simulation results. This difference was attributed to heat loss and 3-dimensionality of heat transfer that was neglected during the calculations. Figure 4-14 shows the temperature contours predicted in the simulation of Mill A-3 sample. This figure shows a temperature gradient inside the inner insulation layer which causes a net heat flow from the top to the bottom section of the insulation layer. This heat flow through the inner insulating wall
neglected in the experimental data analysis is considered to be responsible for over-estimation of the actual thermal conductivity of char samples by 14%.

Figure 4-14  Temperature contours indicating the temperature distribution inside the experimental apparatus (Mill A-3, 500°C simulation, see Chapter 3 for simulation conditions)
If a 14% correction is accounted for in all the thermal conductivity values of char bed materials from the mills, the major data can be re-plotted as shown in Figure 4-15.

![Figure 4-15](image)

**Figure 4-15** Effective thermal conductivity of char bed materials considering the heat loss through the insulating walls (corrected data)

Based on these results, the corrected thermal conductivity data can be correlated as follows:

For $T \leq 500^\circ C$

$$K_{\text{eff}} (W/m^\circ C) = 0.21$$

For $T > 500^\circ C$

$$K_{\text{eff}} (W/m^\circ C) = 0.0035 T - 1.54$$

where $T$ is specified in $^\circ C$.  

(4-2)

As indicated in Figure 4-15, all the experimental data points fall within $\pm 30\%$ of the correlation.
5.1 Conclusions

In summary, an experimental apparatus was designed and constructed to measure the effective thermal conductivity of char bed materials obtained from different mills, and char samples made in the laboratory. A computational fluid dynamics code was used to simulate the flow of heat in the char sample in the experimental apparatus. Based on the experiments and numerical analysis the following conclusions can be drawn:

1. The effective thermal conductivity of all samples examined has a similar temperature dependence despite the wide difference in sample porosity and structure.

2. A thermal conductivity value of 0.21 W/m°C is suggested for char bed materials below 500°C. At temperatures above 500°C the effective thermal conductivity of char increased from 0.21 W/m°C at 500°C to 0.91 W/m°C at 700°C. Based on the experimental data, a two-part correlation was developed as follows:

\[ k_{\text{eff}} \text{ (W/m°C)} = 0.21 \quad \text{for } T \leq 500°C \]
\[ k_{\text{eff}} \text{ (W/m°C)} = 0.0035 T - 1.54 \quad \text{for } T > 500°C. \]

3. The increase in thermal conductivity beyond 500°C is believed to be due to sintering and melting of smelt, radiation heat transfer through porous char materials.
4. The thermal conductivity model recommended by Richardson and Merriam (1977) did not predict well the measured thermal conductivity of char bed materials, even if the porosity and pore size were adjusted for each sample.

5.2 Recommendations

This project is part of an ongoing study focused on understanding the cooling process of char beds in recovery boilers. The ultimate objective of this project is to minimize the downtime of recovery boilers by reducing the time it takes for the char bed to cool following a shutdown. The thermal conductivity data obtained in this work are mainly useful for numerically simulating the cooling of char bed. However, there are other factors such as bed mass and bed heat content that need to be better understood before such modeling can be done. Unlike the cooling of a uniform hot object in a known surrounding, the cooling of char bed is extremely difficult to model because chemical reactions and combustion can take place in the char bed. The shape of the bed is non-uniform, temperatures at different locations vary, and there are hot molten smelt pockets throughout the bed. Figure 5-1 indicates the temperatures in various locations inside the char bed following an emergency shutdown procedure, started at approximately 21:30.
Figure 5-1  Temperature history at various locations in a char bed following a simulated emergency shutdown procedure (shutdown was started at 21:00)

The different lines in the figure represent the temperature histories in various locations in the bed. The sudden increase in the temperature is believed to be due to combustion taking place at or near the location of the thermocouple. As indicated by the data, the cooling of a char bed is much more complicated than just cooling of a hot object. It is hence necessary to understand the characteristics of the char bed in more detail before any attempt can be made in realistically modeling the cooling process.
REFERENCES


4. CHAM.TR100A *Guide to the PHOENICS Input Language*.


Heat transfer from the horizontal walls of the experimental apparatus due to natural convection results in a three-dimensional heat flow and affects the char sample thermal conductivity values measured. In order to verify that the heat loss was negligible, total heat transfer from the horizontal walls due to natural convection was calculated using the following correlations (Incropera et al., 1996)

Grashof number, which is the ratio of buoyancy force to the viscous force acting on the fluid, was defined by Equation A-1.

\[
Gr_L = \frac{g \beta (T_s - T_x) L^3}{\nu^2} \quad (A-1)
\]

where

- \( Gr_L \): Grashof number
- \( g \): acceleration due to gravity (m/s\(^2\))
- \( \beta \): volumetric thermal expansion coefficient (K\(^{-1}\))
- \( T_s \): wall surface temperature (°C)
- \( T_x \): surrounding temperature (°C)
- \( L \): vertical height of the wall (m)
- \( \nu \): viscosity of surrounding fluid (m\(^2\)/s)
Rayleigh number was defined by Equation A-2.

\[ \text{Ra}_L = \text{Gr}_L \text{Pr} \]  \hspace{1cm} (A-2)

where

- \( \text{Ra}_L \) Rayleigh number
- \( \text{Gr}_L \) Grashof number
- \( \text{Pr} \) Prandtl number

Nusselt number was defined by Equation A-3.

\[ \text{Nu}_L = 0.68 + 0.670 \left( \frac{\text{Ra}_L}{10^9} \right) \left[ 1+(0.492/\text{Pr})^{9/16} \right]^{4/9} \]  \hspace{1cm} (A-3)

(for \( \text{Ra}_L \leq 10^9 \))

Convection heat transfer coefficient was related to Nusselt number by Equation A-4.

\[ h = k \frac{\text{Nu}_L}{L} \]  \hspace{1cm} (A-4)

where

- \( h \) convection heat transfer coefficient (W/m\(^2\).K)
- \( k \) thermal conductivity (W/m.K)
- \( L \) vertical height of the wall (m)
Heat transfer due to convection was calculated using Equation A-5.

\[ q = h (T_s - T_\infty) \quad \text{(A-5)} \]

where \( q \) is convection heat transfer in W/m\(^2\).

Air Properties at 300 K:

- \( \beta \) = \( 3.33 \times 10^{-3} \) (K\(^{-1}\))
- \( v \) = \( 15.89 \times 10^{-6} \) (m\(^2\)/s)
- \( \text{Pr} \) = 0.707
- \( k \) = \( 26.3 \times 10^{-3} \) (W/mK)

During the experiments room temperature was approximately 25°C. The surface temperature of the apparatus wall was, at most, 10°C higher than the surrounding temperature.

It was assumed that the surrounding air behaved as an ideal gas. Therefore the expansion coefficient was simply the inverse of the temperature. This is a reasonable assumption since air was at room temperature and atmospheric pressure. Also, the surface of the walls was assumed to be isothermal since the temperature variation on the wall was negligible, maximum 2°C.

Using air properties at 300 K, vertical height of wall equal to 0.28 m. and the above assumptions, the total heat transfer due to convection from the walls was calculated.

\[ \text{Gr}_L = 9.8 \text{ m/s}^2 \times 3.33 \times 10^{-3} \text{ K}^{-1} \ (35-25) \text{ K} \ (0.28)^3 \text{ m}^3 / (15.89 \times 10^{-6} \text{ m}^2/\text{s})^2 \]
\[ = 2.84 \times 10^7 \]

\[ \text{Ra}_L = 2.84 \times 10^7 \times 0.707 \]
\[ = 2.0 \times 10^7 \]
Since $Ra_L \leq 10^9$.

$$Nu_L = 0.68 + 0.670 \left(2.0 \times 10^7\right)^{1/4} \left[1+(0.492 / 0.707)^{0.16}\right]^{1.9}$$

$$= 35.1$$

$$h = 26.3 \times 10^{-3} \text{ W/m.K} \times 35.1 / 0.28 \text{ m}$$

$$= 3.30 \text{ W/m}^2\text{K}$$

$$q = 3.30 \text{ W/m}^2\text{K} \ (35-25) \ ^\circ\text{C}$$

$$= 33 \text{ W/m}^2$$

The minimum amount of heat transferred vertically through the char sample was 539 W/m². This happened when the temperature set point was 250°C for Lab-1 sample.

Therefore the maximum heat loss from the vertical insulating walls was found to be 6% of the total heat flow.
TALK=T;RUN( 1, 1)

******************************************************************************
QI created by VDI menu, Version 3.3, Date 03/05/00
CPVNAM=VDI;SPPNAM=Core
******************************************************************************
IRUNN =  1 ;LIBREF =  55
******************************************************************************
Group 1. Run Title
TEXT(Firebrick, 600 C, constant k)
******************************************************************************
Group 2. Transience
STEADY =  T
******************************************************************************
Groups 3, 4, 5 Grid Information
  * Overall number of cells, RSET(M,NX,NY,NZ,tolerance)
RSET(M,40,40,120)
  * Set overall domain extent:
  * xulast yvlast zwlast
name
XSI= 4.380000E-01; YSI= 4.380000E-01; ZSI= 3.590000E-01
RSET(D,CHAM )
******************************************************************************
Group 6. Body-Fitted coordinates
******************************************************************************
Group 7. Variables: STOREd,SOLVEd,NAMEd
ONEPHS =  T
  * Non-default variable names
NAME(149) =KOND ; NAME(150) =TEM1
  * Solved variables list
SOLVE(TEM1)
  * Stored variables list
STORE(KOND)
  * Additional solver options
SOLUTN(TEM1,Y,Y,Y,N,N,Y)
******************************************************************************
Group 8. Terms & Devices
TERMS (TEM1,Y,Y,Y,Y,Y)
******************************************************************************
Group 9. Properties
SETPRPS(1, 0)
RH01 = 1.189000E+00
PRESS0 = 1.000000E+05
TEMPO = 2.730000E+02
CP1 = 1.005000E+03
ENUL = 1.544000E-05 ;ENUT = 0.000000E+00
DV01DT = 3.410000E-03
PRNDTL(TEM1) = -4.400000E-01
******************************************************************************
Group 10. Inter-Phase Transfer Processes
******************************************************************************
GVIEWS \( P, 0.000000E+00, -1.000000E+00, 0.000000E+00 \)
GVIEWS \( UP, 0.000000E+00, 0.000000E+00, 1.000000E+00 \)

> DOM, SIZE, 4.380000E-01, 4.380000E-01, 3.590000E-01
> DOM, MONIT, 2.265000E-01, 2.265000E-01, 1.543000E-01
> DOM, SCALE, 1.000000E+00, 1.000000E+00, 1.000000E+00
> DOM, SNAPSHOT, 1.000000E+02
> GRID, RSET Z_4, 50, 1.000000E+00
> DOM, RELAX, 5.000000E-01

> OBJ1, NAME, B1
> OBJ1, POSITION, 0.000000E+00, 0.000000E+00, 0.000000E+00
> OBJ1, SIZE, 4.380000E-01, 4.380000E-01, 2.750000E-01
> OBJ1, CLIPART, cube14
> OBJ1, ROTATION24, 1
> OBJ1, TYPE, BLOCKAGE
> OBJ1, MATERIAL, 161
> OBJ1, ADIABATIC, 0.000000E+00, 0.000000E+00
> OBJ1, INIT TEMP, 2.500000E+01

> OBJ2, NAME, B2
> OBJ2, POSITION, 7.600000E-02, 7.600000E-02, 0.000000E+00
> OBJ2, SIZE, 2.860000E-01, 2.860000E-01, 3.590000E-01
> OBJ2, CLIPART, cube14
> OBJ2, ROTATION24, 1
> OBJ2, TYPE, BLOCKAGE
> OBJ2, MATERIAL, 162
> OBJ2, ADIABATIC, 0.000000E+00, 0.000000E+00
> OBJ2, INIT TEMP, 2.500000E+01

> OBJ3, NAME, CHAR
> OBJ3, POSITION, 1.400000E-01, 1.400000E-01, 7.500000E-02
> OBJ3, SIZE, 1.580000E-01, 1.580000E-01, 1.300000E-01
> OBJ3, CLIPART, cube1
> OBJ3, ROTATION24, 1
> OBJ3, TYPE, BLOCKAGE
> OBJ3, MATERIAL, -1
> OBJ3, ADIABATIC, 0.000000E+00, 0.000000E+00
> OBJ3, INIT TEMP, 2.500000E+01
> OBJ3, SCAL FIX, 0.000000E+00
> OBJ3, INIT VEL X_1, 0.000000E+00
> OBJ3, INIT VEL Y_1, 0.000000E+00
> OBJ3, INIT VEL Z_1, 0.000000E+00

> OBJ4, NAME, COOLER
> OBJ4, POSITION, 1.400000E-01, 1.400000E-01, 5.800000E-02
> OBJ4, SIZE, 1.580000E-01, 1.580000E-01, 1.700000E-02
> OBJ4, CLIPART, cube4
> OBJ4, ROTATION24, 1
> OBJ4, TYPE, BLOCKAGE
> OBJ4, MATERIAL, 111


Group 11. Initialise Var/Porosity Fields
FIINIT(KOND) = 6.000000E-01; FIINIT(TEM1) = 2.500000E+01
No PATCHes used for this Group

INIADD = F

Group 12. Convection and diffusion adjustments
No PATCHes used for this Group

Group 13. Boundary & Special Sources
No PATCHes used for this Group

Group 14. Downstream Pressure For PARAB

Group 15. Terminate Sweeps
LSWEEP = 60
PESFAC = 1.000000E-03

Group 16. Terminate Iterations

Group 17. Relaxation

Group 18. Limits

Group 19. EARTH Calls To GROUND Station
USEGRD = T; USEGRX = T
ASAP = T

Group 20. Preliminary Printout
ECHO = T

Group 21. Print-out of Variables

Group 22. Monitor Print-Out
IXMON = 22; IYMON = 22; IZMON = 54
NPRMON = 100000
NPRMNT = 1
TSTSWP = -1

Group 23. Field Print-Out & Plot Control
NPRINT = 100000
ISWPRF = 1; ISWPRL = 100000
IPROF = 3

PATCH (T1 , PROFIL, 7, 0, 0, 0, 0, 0, 1, 1)
PLOT (T1 , KOND, 0.000000E+00, 0.000000E+00)
PLOT (T1 , TEM1, 0.000000E+00, 0.000000E+00)

Group 24. Dumps For Restarts
SWIPE = T
> OBJ4, HEAT_FLUX, 0.000000E+00,-6.210000E+01
> OBJ4, INIT_TEMP, 2.500000E+01

> OBJ5, NAME, HEATER
> OBJ5, POSITION, 1.400000E-01, 1.400000E-01, 2.050000E-01
> OBJ5, SIZE, 1.580000E-01, 1.580000E-01, 1.500000E-02
> OBJ5, CLIPART, cube4
> OBJ5, ROTATION24, 1
> OBJ5, TYPE, BLOCKAGE
> OBJ5, MATERIAL, 111
> OBJ5, FIXED_TEMP, 0.000000E+00, 6.200000E+02

> OBJ6, NAME, AIR
> OBJ6, POSITION, 1.400000E-01, 1.400000E-01, 2.200000E-01
> OBJ6, SIZE, 1.580000E-01, 1.580000E-01, 3.500000E-02
> OBJ6, CLIPART, cube1
> OBJ6, ROTATION24, 1
> OBJ6, TYPE, BLOCKAGE
> OBJ6, MATERIAL, 2
> OBJ6, ADIABATIC, 0.000000E+00, 0.000000E+00
> OBJ6, INIT_TEMP, 2.500000E+01
> OBJ6, SCAL_FIXF, 0.000000E+00

> OBJ7, NAME, T1
> OBJ7, POSITION, 2.190000E-01, 2.190000E-01, 7.500000E-02
> OBJ7, SIZE, 2.000000E-03, 2.000000E-03, 1.300000E-01
> OBJ7, CLIPART, default
> OBJ7, ROTATION24, 1
> OBJ7, TYPE, USER_DEFINED

> OBJ8, NAME, TOP
> OBJ8, POSITION, 0.000000E+00, 3.000000E+00, 3.590000E-01
> OBJ8, SIZE, 4.380000E-01, 4.380000E-01, 0.000000E+00
> OBJ8, CLIPART, cube13
> OBJ8, ROTATION24, 1
> OBJ8, TYPE, PLATE
> OBJ8, LINR_HEAT, 3.300000E+00, 2.500000E+01

> OBJ9, NAME, BOTTOM
> OBJ9, POSITION, 0.000000E+00, 0.000000E+00, 0.000000E+00
> OBJ9, SIZE, 4.380000E-01, 4.380000E-01, 0.000000E+00
> OBJ9, CLIPART, cube13
> OBJ9, ROTATION24, 1
> OBJ9, TYPE, PLATE
> OBJ9, LINR_HEAT, 3.300000E+00, 2.500000E+01

> OBJ10, NAME, SIDEX1
> OBJ10, POSITION, 0.000000E+00, 0.000000E+00, 0.000000E+00
> OBJ10, SIZE, 0.000000E+00, 4.380000E-01, 3.590000E-01
> OBJ10, CLIPART, cube13
> OBJ10, ROTATION24, 1
> OBJ10, TYPE, PLATE
> OBJ10, LINR_HEAT, 3.300000E+00, 2.500000E+01
> OBJ11, NAME, SIDEX2
> OBJ11, POSITION, 4.380000E-01, 0.000000E+00, 0.000000E+00
> OBJ11, SIZE, 0.000000E+00, 4.380000E-01, 3.590000E-01
> OBJ11, CLIPART, cube13
> OBJ11, ROTATION24, 1
> OBJ11, TYPE, PLATE
> OBJ11, LINR_HEAT, 3.300000E+00, 2.500000E+01
> OBJ12, NAME, SIDEX1
> OBJ12, POSITION, 0.000000E+00, 0.000000E+00, 0.000000E+00
> OBJ12, SIZE, 4.380000E-01, 0.000000E+00, 3.590000E-01
> OBJ12, CLIPART, cube13
> OBJ12, ROTATION24, 1
> OBJ12, TYPE, PLATE
> OBJ12, LINR_HEAT, 3.300000E+00, 2.500000E+01
> OBJ13, NAME, SIDEX2
> OBJ13, POSITION, 0.000000E+00, 4.380000E-01, 0.000000E+00
> OBJ13, SIZE, 4.380000E-01, 0.000000E+00, 3.590000E-01
> OBJ13, CLIPART, cube13
> OBJ13, ROTATION24, 1
> OBJ13, TYPE, PLATE
> OBJ13, LINR_HEAT, 3.300000E+00, 2.500000E+01
> OBJ14, NAME, TOP1AIR
> OBJ14, POSITION, 0.000000E+00, 0.000000E+00, 2.750000E-01
> OBJ14, SIZE, 4.380000E-01, 7.600000E-02, 8.399999E-02
> OBJ14, CLIPART, cubet
> OBJ14, ROTATION24, 1
> OBJ14, TYPE, BLOCKAGE
> OBJ14, MATERIAL, 2
> OBJ14, ADIABATIC, 0.000000E+00, 0.000000E+00
> OBJ14, INI_TEMP, 2.500000E+01
> OBJ14, SCAL_FIXF, 0.000000E+00
> OBJ15, NAME, TOP2AIR
> OBJ15, POSITION, 0.000000E+00, 3.620000E-01, 2.750000E-01
> OBJ15, SIZE, 4.380000E-01, 7.600000E-02, 9.400000E-02
> OBJ15, CLIPART, cubet
> OBJ15, ROTATION24, 1
> OBJ15, TYPE, BLOCKAGE
> OBJ15, MATERIAL, 2
> OBJ15, ADIABATIC, 0.000000E+00, 0.000000E+00
> OBJ15, INI_TEMP, 2.500000E+01
> OBJ15, SCAL_FIXF, 0.000000E+00
> OBJ16, NAME, TOP3AIR
> OBJ16, POSITION, 0.000000E+00, 7.600000E-02, 2.750000E-01
> OBJ16, SIZE, 7.600000E-02, 2.860000E-01, 8.399999E-02
> OBJ16, CLIPART, cubet
> OBJ16, ROTATION24, 1
> OBJ16, TYPE, BLOCKAGE
> OBJ16, MATERIAL, 2
> OBJ16, ADIABATIC, 0.000000E+00, 0.000000E+00
> OBJ16, INI_TEMP, 2.500000E+01
> OBJ16, SCAL_FIXF, 0.000000E+00

> OBJ17, NAME, TOP4AIR
> OBJ17, POSITION, 3.620000E-01, 7.600000E-02, 2.750000E-01
> OBJ17, SIZE, 7.600000E-02, 2.860000E-01, 8.399999E-02
> OBJ17, CLIPART, cubet
> OBJ17, ROTATION24, 1
> OBJ17, TYPE, BLOCKAGE
> OBJ17, MATERIAL, 2
> OBJ17, ADIABATIC, 0.000000E+00, 0.000000E+00
> OBJ17, INI_TEMP, 2.500000E+01
> OBJ17, SCAL_FIXF, 0.000000E+00

> OBJ18, NAME, AIRBOT
> OBJ18, POSITION, 1.400000E-01, 1.400000E-01, 5.100000E-02
> OBJ18, SIZE, 1.580000E-01, 1.580000E-01, 7.000000E-03
> OBJ18, CLIPART, cubet
> OBJ18, ROTATION24, 1
> OBJ18, TYPE, BLOCKAGE
> OBJ18, MATERIAL, 2
> OBJ18, ADIABATIC, 0.000000E-00, 0.000000E+00
> OBJ18, INI_TEMP, 2.500000E+01
> OBJ18, SCAL_FIXF, 0.000000E+00
STOP
**Group 1. Run Title**

**TEXT (Firebrick, 700°C, constant k) [710, k=0.45]**

**Group 2. Transience**

**STEADY = T**

**Groups 3, 4, 5 Grid Information**

- Overall number of cells, RSET(M,NX,NY,NZ,tolerance)

  **RSET(M,40,40,120)**

- Set overall domain extent:

  **XSI= 4.380000E-01; YSI= 4.380000E-01; ZSI= 3.590000E-01**

**Group 6. Body-Fitted coordinates**

**Group 7. Variables: STOREd, SOLVEd, NAMEd**

**ONEPHS = T**

- Non-default variable names

  **NAME(149) = KOND ; NAME(150) = TEM1**

- Solved variables list

  **SOLVE(TEM1)**

- Stored variables list

  **STORE(KOND)**

- Additional solver options

  **SOLUTN(TEM1,Y,Y,Y,N,N,Y)**

**Group 8. Terms & Devices**

**TERMS (TEM1,Y,Y,Y,Y,Y)**

**Group 9. Properties**

**SETPRPS(1, 0)**

- **RH01 = 1.189000E+00**
- **PRESS0 = 1.000000E+05**
- **TEMPO = 2.730000E+02**
- **CP1 = 1.005000E+03**
- **ENUL = 1.544000E-05 ; ENUT = 0.000000E+00**
- **DV01DT = 3.410000E-03**
- **PRNDTL(TEM1) = -4.500000E-01**

**Group 10. Inter-Phase Transfer Processes**
Group 11. Initialise Var/Porosity Fields
FIINIT(KOND) = 6.000000E-01 ;FIINIT(TEMI) = 2.500000E+01
No PATCHes used for this Group

INIADD = F

-----------------------------------------------

Group 12. Convection and diffusion adjustments
No PATCHes used for this Group

-----------------------------------------------

Group 13. Boundary & Special Sources
No PATCHes used for this Group

-----------------------------------------------

Group 14. Downstream Pressure For PARAB

-----------------------------------------------

Group 15. Terminate Sweeps
LSWEEP = 60
RESFAC = 1.000000E-03

-----------------------------------------------

Group 16. Terminate Iterations

-----------------------------------------------

Group 17. Relaxation

-----------------------------------------------

Group 18. Limits

-----------------------------------------------

Group 19. EARTH Calls To GROUND Station
USEGRD = T ;USEGRX = T
ASAP = T

-----------------------------------------------

Group 20. Preliminary Printout
ECHO = T

-----------------------------------------------

Group 21. Print-out of Variables

-----------------------------------------------

Group 22. Monitor Print-Out
IXMON = 22 ;IYMON = 22 ;IZMON = 54
NPRMON = 100000
NPRMNT = 1
TSTSWP = -1

-----------------------------------------------

Group 23. Field Print-Out & Plot Control
NPRINT = 100000
ISWPRL = 100000
ISWPRF = 1
IPROF = 3

PATCH (T1 ,PROFIL,7,0,0,0,0,0,0,1,1)
    PLOT(T1 ,KOND, 0.000000E+00, 0.000000E+00)
    PLOT(T1 ,TEMI, 0.000000E+00, 0.000000E+00)

-----------------------------------------------

Group 24. Dumps For Re却arts
NOWIPE = T
GVIEW(P, 0.000000E+00, -1.000000E+00, 0.000000E+00)
GVIEW(UP, 0.000000E+00, 0.000000E+00, 1.000000E+00)

> DOM, SIZE, 4.380000E-01, 4.380000E-01, 3.590000E-01
> DOM, MONIT, 2.265000E-01, 2.265000E-01, 1.543000E-01
> DOM, SCALE, 1.000000E+00, 1.000000E+00, 1.000000E+00
> DOM, SNAPSIZE, 1.000000E-02
> GRID, RSET_Z_4, 50, 1.000000E+00
> DOM, RELAX, 5.000000E-01

> OBJ1, NAME, B1
> OBJ1, POSITION, 0.000000E+00, 0.000000E+00, 0.000000E+00
> OBJ1, SIZE, 4.380000E-01, 4.380000E-01, 2.750000E-01
> OBJ1, CLIPART, cube14
> OBJ1, ROTATION24, 1
> OBJ1, TYPE, BLOCKAGE
> OBJ1, MATERIAL, 161
> OBJ1, ADIABATIC, 1.000000E+00, 0.000000E+00
> OBJ1, INI_TEMP, 2.500000E+01

> OBJ2, NAME, B2
> OBJ2, POSITION, 7.600000E-02, 7.600000E-02, 0.000000E+00
> OBJ2, SIZE, 2.860000E-01, 2.860000E-01, 3.590000E-01
> OBJ2, CLIPART, cube14
> OBJ2, ROTATION24, 1
> OBJ2, TYPE, BLOCKAGE
> OBJ2, MATERIAL, 162
> OBJ2, ADIABATIC, 0.000000E+00, 0.000000E+00
> OBJ2, INI_TEMP, 2.500000E+01

> OBJ3, NAME, CHAR
> OBJ3, POSITION, 1.400000E-01, 1.400000E-01, 7.500000E-02
> OBJ3, SIZE, 1.580000E-01, 1.580000E-01, 1.300000E-01
> OBJ3, CLIPART, cube1
> OBJ3, ROTATION24, 1
> OBJ3, TYPE, BLOCKAGE
> OBJ3, MATERIAL, -1
> OBJ3, ADIABATIC, 0.000000E+00, 0.000000E+00
> OBJ3, INI_TEMP, 2.500000E+01
> OBJ3, SCAL_FIXF, 0.000000E+00
> OBJ3, INI_VEL_X_1, 0.000000E+00
> OBJ3, INI_VEL_Y_1, 0.000000E+00
> OBJ3, INI_VEL_Z_1, 0.000000E+00

> OBJ4, NAME, COOLER
> OBJ4, POSITION, 1.400000E-01, 1.400000E-01, 5.800000E-02
> OBJ4, SIZE, 1.580000E-01, 1.580000E-01, 1.700000E-02
> OBJ4, CLIPART, cube4
> OBJ4, ROTATION24, 1
> OBJ4, TYPE, BLOCKAGE
> OBJ4, MATERIAL, 111
> OBJ4, HEAT_FLUX, 0.000000E+00, -6.830000E+01
> OBJ4, INI_TEMP, 2.500000E+01

> OBJ5, NAME, HEATER
> OBJ5, POSITION, 1.400000E-01, 1.400000E-01, 2.050000E-01
> OBJ5, SIZE, 1.580000E-01, 1.580000E-01, 1.500000E-02
> OBJ5, CLIPART, cube4
> OBJ5, ROTATION24, 1
> OBJ5, TYPE, BLOCKAGE
> OBJ5, MATERIAL, 111
> OBJ5, FIXED_TEMP, 0.000000E+00, 7.100000E+02

> OBJ6, NAME, AIR
> OBJ6, POSITION, 1.400000E-01, 1.400000E-01, 2.200000E-01
> OBJ6, SIZE, 1.580000E-01, 1.580000E-01, 3.500000E-02
> OBJ6, CLIPART, cube
> OBJ6, ROTATION24, 1
> OBJ6, TYPE, BLOCKAGE
> OBJ6, MATERIAL, 2
> OBJ6, ADIABATIC, 0.000000E-00, 0.000000E+00
> OBJ6, INI_TEMP, 2.500000E-01
> OBJ6, SCALE_FIXF, 0.000000E+00

> OBJ7, NAME, T1
> OBJ7, POSITION, 2.190000E-01, 2.190000E-01, 7.500000E-01
> OBJ7, SIZE, 2.000000E-03, 2.000000E-03, 1.300000E-01
> OBJ7, CLIPART, default
> OBJ7, ROTATION24, 1
> OBJ7, TYPE, USER_DEFINED

> OBJ8, NAME, TOP
> OBJ8, POSITION, 0.000000E+00, 3.000000E+00, 3.590000E-01
> OBJ8, SIZE, 4.380000E-01, 4.380000E-01, 0.000000E+00
> OBJ8, CLIPART, cube13
> OBJ8, ROTATION24, 1
> OBJ8, TYPE, PLATE
> OBJ8, LINR_HEAT, 3.300000E-00, 2.500000E+01

> OBJ9, NAME, BOTTOM
> OBJ9, POSITION, 0.000000E+00, 0.000000E+00, 0.000000E+00
> OBJ9, SIZE, 4.380000E-01, 4.380000E-01, 0.000000E+00
> OBJ9, CLIPART, cube13
> OBJ9, ROTATION24, 1
> OBJ9, TYPE, PLATE
> OBJ9, LINR_HEAT, 3.300000E+00, 2.500000E+01

> OBJ10, NAME, SIDEX1
> OBJ10, POSITION, 0.000000E+00, 0.000000E+00, 0.000000E+00
> OBJ10, SIZE, 0.000000E+00, 4.380000E-01, 3.590000E-01
> OBJ10, CLIPART, cube13
> OBJ10, ROTATION24, 1
> OBJ10, TYPE, PLATE
> OBJ10, LINR_HEAT, 3.300000E+00, 2.500000E+01
> OBJ11, NAME, SIDEY2
> OBJ11, POSITION, 4.380000E-01, 0.000000E+00, 0.000000E+00
> OBJ11, SIZE, 3.000000E+00, 4.380000E-01, 3.590000E-01
> OBJ11, CLIPART, cube13
> OBJ11, ROTATION24, 1
> OBJ11, TYPE, PLATE
> OBJ11, LINR_HEAT, 3.300000E+00, 2.500000E+01

> OBJ12, NAME, SIDEY1
> OBJ12, POSITION, 0.000000E+00, 3.000000E+00, 0.000000E+00
> OBJ12, SIZE, 4.380000E-01, 3.000000E+00, 3.590000E-01
> OBJ12, CLIPART, cube13
> OBJ12, ROTATION24, 1
> OBJ12, TYPE, PLATE
> OBJ12, LINR_HEAT, 3.300000E+00, 2.500000E+01

> OBJ13, NAME, SIDEY2
> OBJ13, POSITION, 1.000000E+00, 4.380000E-01, 0.000000E+00
> OBJ13, SIZE, 1.000000E-01, 3.000000E+00, 3.590000E+01
> OBJ13, CLIPART, cube13
> OBJ13, ROTATION24, 1
> OBJ13, TYPE, PLATE
> OBJ13, LINR_HEAT, 3.300000E+00, 2.500000E+01

> OBJ14, NAME, TOP1AIR
> OBJ14, POSITION, 0.000000E+00, 0.000000E+00, 2.750000E-01
> OBJ14, SIZE, 4.380000E-01, 1.600000E-02, 3.399999E-02
> OBJ14, CLIPART, cube
> OBJ14, ROTATION24, 1
> OBJ14, TYPE, BLOCKAGE
> OBJ14, MATERIAL, 2
> OBJ14, ADIABATIC, 0.600000E+00, 2.000000E+00
> OBJ14, INI_TEMP, 2.500000E+01
> OBJ14, SCAL_FIXF, 0.600000E+00

> OBJ15, NAME, TOP2AIR
> OBJ15, POSITION, 0.000000E+00, 3.620000E-01, 2.750000E-01
> OBJ15, SIZE, 4.380000E-01, 1.600000E-02, 3.400000E-02
> OBJ15, CLIPART, cube
> OBJ15, ROTATION24, 1
> OBJ15, TYPE, BLOCKAGE
> OBJ15, MATERIAL, 2
> OBJ15, ADIABATIC, 0.000000E+00, 0.000000E+00
> OBJ15, INI_TEMP, 2.500000E+01
> OBJ15, SCAL_FIXF, 0.000000E+00

> OBJ16, NAME, TOP3AIR
> OBJ16, POSITION, 0.000000E+00, 7.600000E-02, 2.750000E-01
> OBJ16, SIZE, 7.600000E-02, 2.860000E-01, 8.399999E-02
> OBJ16, CLIPART, cube
> OBJ16, ROTATION24, 1
> OBJ16, TYPE, BLOCKAGE
> OBJ16, MATERIAL, 2
> OBJ16, ADIABATIC, 0.000000E+00, 0.000000E+00
> OBJ16, INI_TEMP, 2.500000E+01
> OBJ16, SCAL_FIXF, 0.000000E+00
>
> OBJ17, NAME, TOP4AIR
> OBJ17, POSITION, 3.620000E-01, 7.600000E-02, 2.750000E-01
> OBJ17, SIZE, 7.600000E-02, 2.860000E-01, 9.399999E-02
> OBJ17, CLIPART, cubet
> OBJ17, ROTATION24, 1
> OBJ17, TYPE, BLOCKAGE
> OBJ17, MATERIAL, 2
> OBJ17, ADIABATIC, 0.000000E+00, 0.000000E+00
> OBJ17, INI_TEMP, 2.500000E+01
> OBJ17, SCAL_FIXF, 0.000000E+00
>
> OBJ18, NAME, AIRBOT
> OBJ18, POSITION, 1.400000E-01, 1.400000E-01, 5.100000E-02
> OBJ18, SIZE, 1.580000E-01, 1.580000E-01, 7.000000E-03
> OBJ18, CLIPART, cubet
> OBJ18, ROTATION24, 1
> OBJ18, TYPE, BLOCKAGE
> OBJ18, MATERIAL, 2
> OBJ18, ADIABATIC, 0.000000E+00, 0.000000E+00
> OBJ18, INI_TEMP, 2.500000E+01
> OBJ18, SCAL_FIXF, 0.000000E+00

STOP
**Group 1. Run Title**

**TEXT**: Firebrick 800 C, constant k̇ [815, k̇ = 0.45]

**Group 2. Transience**

**STEADY** = T

**Groups 3, 4, 5 Grid Information**

* Overall number of cells, RSET'M,NX, NY, NZ, tolerance

**RSET**: 40, 40, 120

* Set overall domain extent:

  * xlast, ylast, zlast

**KSI** = 4.380000E-01; **YSI** = 4.380000E-01; **ZSI** = 3.590000E-01

**RSET**: CHAM

**Group 6. Body-Fitted coordinates**

**Group 7. Variables: STOREd, SOLVeD, NAMEd**

**ONEPHS** = T

* Non-default variable names

**NAME** (149) = KOND; **NAME** (150) = TEM1

* Solved variables list

**SOLVE** (TEM1)

* Stored variables list

**STORE** (KOND)

* Additional solver options

**SOLVIN** (TEM1, Y, Y, N, N, Y)

**Group 8. Terms & Devices**

**TERMS** (TEM1, Y, Y, Y, Y, Y)

**Group 9. Properties**

**SETPRPS** (1, 0)

**RHO1** = 1.189000E+00

**PRESS0** = 1.000000E+05

**TEMP0** = 2.730000E+02

**CPI** = 1.005000E+03

**ENUL** = 1.544000E-05; **ENUT** = 0.000000E+00

**DV01DT** = 3.410000E-03

**PRNDTL** (TEM1) = -4.500000E-01

**Group 10. Inter-Phase Transfer Processes**

**TALK** = T; **RUN** (1, 1)

Q1 created by VDI menu, Version 3.3, Date 03/05/00

**CPVNAM** = VDI; **SPPNAM** = Core
Group 11. Initialise Var/Porosity Fields
FINIT(KOND) = 6.000000E-01; FINIT(TEM1) = 2.500000E+01
No PATCHes used for this Group

INIADD = F

Group 12. Convection and diffusion adjustments
No PATCHes used for this Group

Group 13. Boundary & Special Sources
No PATCHes used for this Group

Group 14. Downstream Pressure For PARAB

Group 15. Terminate Sweeps
LSWEEP = 60
PESMAC = 1.000000E-03

Group 16. Terminate Iterations

Group 17. Relaxation

Group 18. Limits

Group 19. EARTH Calls To GROUND Station
USEGRD = T; USEGRX = T
ASAP = T

Group 20. Preliminary Printout
ECHO = T

Group 21. Print-out of Variables

Group 22. Monitor Print-Out
IXMON = 22; IYMON = 22; IZMON = 54
NPRMON = 100000
NPRMNT = 1
TSTSWP = -1

Group 23. Field Print-Out & Plot Control
NPRINT = 100000
ISWPRF = 1; ISWPRL = 100000
IPROF = 3

PATCH (T1 , PROFIL, 7, 0, 0, 0, 0, 0, 1, 1)
PLLOT(T1 , KOND, 0.000000E+00, 0.000000E+00)
PLLOT(T1 , TEM1, 0.000000E+00, 0.000000E+00)

Group 24. Dumps For Restarts
NOWIPE = T
GVIEWS(P, 0.000000E+00, -1.000000E+00, 0.000000E+00)
GVIEWS(UP, 0.000000E+00, 0.000000E+00, 0.000000E+00)

> DCM, SIZE, 4.380000E-01, 4.380000E-01, 3.590000E-01
> DCM, MONIT, 2.265000E-01, 2.265000E-01, 1.543000E-01
> DCM, SCALE, 1.000000E+00, 1.000000E+00, 1.000000E+00
> DCM, SNAPSIZE, 1.000000E-02
> GRID, RSET_2_4, 50, 1.000000E+00
> DCM, RELAX, 5.000000E-01

> OBJ1, NAME, B1
> OBJ1, POSITION, 0.000000E+00, 0.000000E+00, 0.000000E+00
> OBJ1, SIZE, 4.380000E-01, 4.380000E-01, 2.750000E-01
> OBJ1, CLIPART, cube14
> OBJ1, ROTATION24, 1
> OBJ1, TYPE, BLOCKAGE
> OBJ1, MATERIAL, 161
> OBJ1, ADIABATIC, 0.000000E+00, 0.000000E+00
> OBJ1, INI_TEMP, 2.500000E+01

> OBJ2, NAME, B2
> OBJ2, POSITION, 7.600000E-02, 7.600000E-02, 0.000000E+00
> OBJ2, SIZE, 2.860000E-01, 2.860000E-01, 3.590000E-01
> OBJ2, CLIPART, cube14
> OBJ2, ROTATION24, 1
> OBJ2, TYPE, BLOCKAGE
> OBJ2, MATERIAL, 162
> OBJ2, ADIABATIC, 0.000000E+00, 0.000000E+00
> OBJ2, INI_TEMP, 2.500000E+01

> OBJ3, NAME, CHAR
> OBJ3, POSITION, 1.400000E-01, 1.400000E-01, 7.500000E-02
> OBJ3, SIZE, 1.580000E-01, 1.580000E-01, 1.300000E-01
> OBJ3, CLIPART, cube14
> OBJ3, ROTATION24, 1
> OBJ3, TYPE, BLOCKAGE
> OBJ3, MATERIAL, -1
> OBJ3, ADIABATIC, 0.000000E+00, 0.000000E+00
> OBJ3, INI_TEMP, 2.500000E+01
> OBJ3, SCAL_FIX, 0.000000E+00
> OBJ3, INI_VEL_X, 0.000000E+00
> OBJ3, INI_VEL_Y, 0.000000E+00
> OBJ3, INI_VEL_Z, 0.000000E+00

> OBJ4, NAME, COOLER
> OBJ4, POSITION, 1.400000E-01, 1.400000E-01, 5.800000E-02
> OBJ4, SIZE, 1.580000E-01, 1.580000E-01, 1.700000E-01
> OBJ4, CLIPART, cube4
> OBJ4, ROTATION24, 1
> OBJ4, TYPE, BLOCKAGE
> OBJ4, MATERIAL, 111
> OBJ4, HEAT_FLUX, 0.000000E+00, -7.940000E-01
> OBJ4, INI_TEMP, 2.500000E+01
> OBJ5, NAME, HEATER
> OBJ5, POSITION, 1.400000E-01, 1.400000E-01, 2.050000E-01
> OBJ5, SIZE, 1.580000E-01, 1.580000E-01, 1.500000E-02
> OBJ5, CLIPART, cube4
> OBJ5, ROTATION24, 1
> OBJ5, TYPE, BLOCKAGE
> OBJ5, MATERIAL, 111
> OBJ5, FIXED_TMP, 0.000000E+00, 8.150000E+02
> OBJ6, NAME, AIR
> OBJ6, POSITION, 1.400000E-01, 1.400000E-01, 2.200000E-01
> OBJ6, SIZE, 1.580000E-01, 1.580000E-01, 3.500000E-02
> OBJ6, CLIPART, cube
> OBJ6, ROTATION24, 1
> OBJ6, TYPE, BLOCKAGE
> OBJ6, MATERIAL, 2
> OBJ6, ADIABATIC, 0.000000E+00, 0.300000E+00
> OBJ6, INI_TEMP, 2.500000E+01
> OBJ6, SCALE_FIXF, 0.000000E+00
> OBJ7, NAME, T1
> OBJ7, POSITION, 2.190000E-01, 2.190000E-01, 3.500000E-02
> OBJ7, SIZE, 2.000000E-03, 2.000000E-03, 1.300000E-01
> OBJ7, CLIPART, default
> OBJ7, ROTATION24, 1
> OBJ7, TYPE, USER_DEFINED
> OBJ8, NAME, TOP
> OBJ8, POSITION, 0.000000E+00, 1.000000E+00, 3.390000E-01
> OBJ8, SIZE, 4.380000E-01, 4.380000E-01, 0.000000E+00
> OBJ8, CLIPART, cube13
> OBJ8, ROTATION24, 1
> OBJ8, TYPE, PLATE
> OBJ8, LINR_HEAT, 3.300000E+00, 2.500000E+01
> OBJ9, NAME, BOTTOM
> OBJ9, POSITION, 0.000000E+00, 0.000000E+00, 3.300000E+00
> OBJ9, SIZE, 4.380000E-01, 4.380000E-01, 0.000000E+00
> OBJ9, CLIPART, cube13
> OBJ9, ROTATION24, 1
> OBJ9, TYPE, PLATE
> OBJ9, LINR_HEAT, 3.300000E+00, 2.500000E+01
> OBJ10, NAME, SIDEX1
> OBJ10, POSITION, 0.000000E+00, 0.000000E+00, 3.000000E+00
> OBJ10, SIZE, 0.000000E+00, 4.380000E-01, 3.590000E-01
> OBJ10, CLIPART, cube13
> OBJ10, ROTATION24, 1
> OBJ10, TYPE, PLATE
> OBJ10, LINR_HEAT, 3.300000E+00, 2.500000E+01
> OBJ11, NAME, SIDEY2
> OBJ11, POSITION, 0.000000E+00, 0.000000E+00, 0.000000E+00
> OBJ11, SIZE, 0.000000E+00, 4.380000E-01, 0.000000E+00, 3.590000E-01
> OBJ11, CLIPART, cube13
> OBJ11, ROTATION24, 1
> OBJ11, TYPE, PLATE
> OBJ11, LINR_HEAT, 3.300000E+00, 2.500000E+01
> OBJ12, NAME, SIDEY1
> OBJ12, POSITION, 0.000000E+00, 0.000000E+00, 0.000000E+00
> OBJ12, SIZE, 0.000000E+00, 4.380000E-01, 0.000000E+00, 3.590000E-01
> OBJ12, CLIPART, cube13
> OBJ12, ROTATION24, 1
> OBJ12, TYPE, PLATE
> OBJ12, LINR_HEAT, 3.300000E+00, 2.500000E+01
> OBJ13, NAME, SIDEY2
> OBJ13, POSITION, 0.000000E+00, 4.380000E-01, 0.000000E+00
> OBJ13, SIZE, 0.000000E+00, 4.380000E-01, 0.000000E+00, 3.590000E-01
> OBJ13, CLIPART, cube13
> OBJ13, ROTATION24, 1
> OBJ13, TYPE, PLATE
> OBJ13, LINR_HEAT, 3.300000E+00, 2.500000E+01
> OBJ14, NAME, TOP1AIR
> OBJ14, POSITION, 0.000000E+00, 0.000000E+00, 2.750000E-01
> OBJ14, SIZE, 0.000000E+00, 4.380000E-01, 0.000000E-02, 3.999999E-02
> OBJ14, CLIPART, cube1
> OBJ14, ROTATION24, 1
> OBJ14, TYPE, BLOCKAGE
> OBJ14, MATERIA, 0.000000E+00, 0.000000E+00, 0.000000E+00
> OBJ14, INI_TEMP, 2.500000E-01
> OBJ14, SCAL_FIXF, 0.000000E+00
> OBJ15, NAME, TOP2AIR
> OBJ15, POSITION, 0.000000E+00, 3.620000E-01, 2.750000E-01
> OBJ15, SIZE, 0.000000E+00, 4.380000E-01, 0.000000E-02, 3.400000E-02
> OBJ15, CLIPART, cube1
> OBJ15, ROTATION24, 1
> OBJ15, TYPE, BLOCKAGE
> OBJ15, MATERIA, 0.000000E+00, 0.000000E+00, 0.000000E+00
> OBJ15, INI_TEMP, 2.500000E-01
> OBJ15, SCAL_FIXF, 0.000000E+00
> OBJ16, NAME, TOP3AIR
> OBJ16, POSITION, 0.000000E+00, 0.000000E-02, 2.750000E-01
> OBJ16, SIZE, 7.660000E-02, 2.860000E-01, 8.399999E-02
> OBJ16, CLIPART, cube1
> OBJ16, ROTATION24,   1
> OBJ16, TYPE,          BLOCKAGE
> OBJ16, MATERIAL,      2
> OBJ16, ADIABATIC,     0.000000E+00, 0.000000E+00
> OBJ16, INI_TEMP,      2.500000E+01
> OBJ16, SCAL_FIXF,     0.000000E+00

> OBJ17, NAME,          TOP4AIR
> OBJ17, POSITION,      3.620000E-01, 7.600000E-02, 2.750000E-01
> OBJ17, SIZE,          7.600000E-02, 1.860000E-01, 9.399999E-02
> OBJ17, CLIPART,       cubet
> OBJ17, ROTATION24,     1
> OBJ17, TYPE,          BLOCKAGE
> OBJ17, MATERIAL,      2
> OBJ17, ADIABATIC,     0.000000E+00, 0.000000E+00
> OBJ17, INI_TEMP,      2.500000E+01
> OBJ17, SCAL_FIXF,     0.000000E+00

> OBJ18, NAME,          AIRBCT
> OBJ18, POSITION,      1.400000E-01, 1.400000E-01, 5.100000E-02
> OBJ18, SIZE,          1.580000E-01, 1.590000E-01, 1.000000E-03
> OBJ18, CLIPART,       cubet
> OBJ18, ROTATION24,     1
> OBJ18, TYPE,          BLOCKAGE
> OBJ18, MATERIAL,      2
> OBJ18, ADIABATIC,     0.000000E+00, 0.000000E+00
> OBJ18, INI_TEMP,      2.500000E+01
> OBJ18, SCAL_FIXF,     0.000000E+00
STOP
TALK=T;RUN(1,1)

Q1 created by VDI menu, Version 3.3, Date 03/05/00
CPVNAME=VDI;SPPNAME=Core

IRUNN = 1 ; LIBREF = 55

Group 1. Run Title
TEXT(=Firebrick, 900 C, constant k)(0.55, 920)

Group 2. Transience
STEADY = T

Group 3, 4, 5 Grid Information
   * Overall number of cells, RSET(M,NX,NY,NZ,tolerance)
RSET(M,40,40,120)
   * Set overall domain extent:
     XULAST YULAST ZULAST
NAME XSI= 4.390000E-01; YSI= 4.380000E-01; ZSI= 3.590000E-01
RSET('D,CHAM )

Group 6. Body-Fitted coordinates

Group 7. Variables: STOREd,SOLVEd,NAMEd
ONEPHS = T
   * Non-default variable names
NAME(149) = KOND ; NAME(150) = TEM1
   * Solved variables list
SOLVE(TEM1)
   * Stored variables list
STORE(KOND)
   * Additional solver options
SOLUTN(TEM1,Y,Y,Y,N,N,Y)

Group 8. Terms & Devices
TERMS (TEM1,Y,Y,Y,Y,Y,Y)

Group 9. Properties
SETPRPS(1,0)
RHO1 = 1.189000E+00
PRESSO = 1.000000E+05
TEMP0 = 2.730000E+02
CP1 = 1.005000E+03
ENUL = 1.544000E-05 ; ENUT = 0.000000E+00
DVO1DT = 3.410000E-03
PRNDTL(TEM1) = -5.500000E-01

Group 10. Inter-Phase Transfer Processes
Group 11. Initialise Var/Porosity Fields
FIINIT(KOND) = 6.000000E-01; FIINIT(TEM1) = 2.500000E+01
No PATCHes used for this Group

INIADD = F

Group 12. Convection and diffusion adjustments
No PATCHes used for this Group

Group 13. Boundary & Special Sources
No PATCHes used for this Group

Group 14. Downstream Pressure For PARAB

Group 15. Terminate Sweeps
LSWEEP = 60
RESFAC = 1.000000E-03

Group 16. Terminate Iterations

Group 17. Relaxation

Group 18. Limits

Group 19. EARTH Calls To GROUND Station
USEGRD = T; USEGRX = T
ASAP = T

Group 20. Preliminary Printout
ECHO = T

Group 21. Print-out of Variables

Group 22. Monitor Print-Out
IXMON = 22; IYMON = 22; IZMON = 54
NPRMON = 100000
NPRMNT = 1
TSTSWP = -1

Group 23. Field Print-Out & Plot Control
NPRINT = 100000
ISWPRF = 1; ISWPRL = 100000
IPROF = 3

PATCH (T1 ,PROFIL,7,0,0,0,0,0,1,1)
PLOT(T1 ,KOND, 0.000000E+00, 0.000000E+00)
PLOT(T1 ,TEM1, 0.000000E+00, 0.000000E+00)

Group 24. Dumps For Restarts
NOWIPE = T
GVIEW(P,0.000000E+00,-1.000000E+00,0.000000E+00)
GVIEW(UP,0.000000E+00,0.000000E+00,1.000000E+00)

> DOM, SIZE, 4.380000E-01, 4.380000E-01, 3.590000E-01
> DOM, MONIT, 2.265000E-01, 2.265000E-01, 1.543000E-01
> DOM, SCALE, 1.000000E+00, 1.000000E+00, 1.000000E+00
> DOM, SNAPSIZ, 1.000000E-02
> GRID, RSET_Z_4, 50, 1.0000000E+0
> DOM, RELAX, 5.000000E-01

> OBJ1, NAME, B1
> OBJ1, POSITION, 0.000000E+00, 0.000000E+00, 0.000000E+00
> OBJ1, SIZE, 4.380000E-01, 4.380000E-01, 2.750000E-01
> OBJ1, CLIPART, cube14
> OBJ1, ROTATION24, 1
> OBJ1, TYPE, BLOCKAGE
> OBJ1, MATERIAL, 161
> OBJ1, ADIABATIC, 0.000000E+00, 0.000000E+00
> OBJ1, INI_TEMP, 2.500000E+01

> OBJ2, NAME, B2
> OBJ2, POSITION, 7.600000E-02, -7.600000E-02, 0.000000E+00
> OBJ2, SIZE, 2.860000E-01, 2.860000E-01, 3.590000E-01
> OBJ2, CLIPART, cube14
> OBJ2, ROTATION24, 1
> OBJ2, TYPE, BLOCKAGE
> OBJ2, MATERIAL, 162
>OBJ2, ADIABATIC, 0.000000E+00, 0.000000E+00
>OBJ2, INI_TEMP, 2.500000E+01

> OBJ3, NAME, CHAR
> OBJ3, POSITION, 1.400000E-01, 1.400000E-01, 7.500000E-02
>OBJ3, SIZE, 1.580000E-01, 1.580000E-01, 1.300000E-01
> OBJ3, CLIPART, cube1
> OBJ3, ROTATION24, 1
> OBJ3, TYPE, BLOCKAGE
> OBJ3, MATERIAL, -1
> OBJ3, ADIABATIC, 0.000000E+00, 3.000000E+00
> OBJ3, INI_TEMP, 2.500000E+01
> OBJ3, SCAL_FIX, 0.000000E+00
> OBJ3, INI_VEL_X_1, 0.000000E+00
> OBJ3, INI_VEL_Y_1, 0.000000E+00
> OBJ3, INI_VEL_Z_1, 0.000000E+00

> OBJ4, NAME, COOLER
> OBJ4, POSITION, 1.400000E-01, 1.400000E-01, 5.800000E-02
> OBJ4, SIZE, 1.580000E-01, 1.580000E-01, 1.700000E-02
> OBJ4, CLIPART, cube4
> OBJ4, ROTATION24, 1
> OBJ4, TYPE, BLOCKAGE
> OBJ4, MATERIAL, 111
> OBJ4, HEAT_FLUX, 0.000000E+00, -1.010000E+02
> OBJ4, INI_TEMP, 2.500000E+01

> OBJ5, NAME, HEATER
> OBJ5, POSITION, 1.400000E-01, 1.400000E-01, 2.050000E-01
> OBJ5, SIZE, 1.580000E-01, 1.580000E-01, 1.500000E-02
> OBJ5, CLIPART, cube4
> OBJ5, ROTATION24, 1
> OBJ5, TYPE, BLOCKAGE
> OBJ5, MATERIAL, 111
> OBJ5, FIXED_TEMP, 0.000000E+00, 9.200000E+02

> OBJ6, NAME, AIR
> OBJ6, POSITION, 1.400000E-01, 1.400000E-01, 2.200000E-01
> OBJ6, SIZE, 1.580000E-01, 1.580000E-01, 3.500000E-02
> OBJ6, CLIPART, cube1
> OBJ6, ROTATION24, 1
> OBJ6, TYPE, BLOCKAGE
> OBJ6, MATERIAL, 2
> OBJ6, ADIABATIC, 0.000000E+00, 0.000000E+00
> OBJ6, INI_TEMP, 2.500000E+01
> OBJ6, SCAL_FIXT, 0.000000E+00

> OBJ7, NAME, T1
> OBJ7, POSITION, 2.190000E-01, 2.190000E-01, 7.500000E-02
> OBJ7, SIZE, 2.000000E-03, 2.000000E-03, 1.300000E-01
> OBJ7, CLIPART, default
> OBJ7, ROTATION24, 1
> OBJ7, TYPE, USER_DEFINED

> OBJ8, NAME, TOP
> OBJ8, POSITION, 0.000000E+00, 3.000000E+00, 3.590000E-01
> OBJ8, SIZE, 4.380000E-01, 4.380000E-01, 0.000000E+00
> OBJ8, CLIPART, cube13
> OBJ8, ROTATION24, 1
> OBJ8, TYPE, PLATE
> OBJ8, LINR_HEAT, 3.300000E+00, 2.500000E+01

> OBJ9, NAME, BOTTOM
> OBJ9, POSITION, 0.000000E+00, 0.000000E+00, 0.000000E+00
> OBJ9, SIZE, 4.380000E-01, 4.380000E-01, 0.000000E+00
> OBJ9, CLIPART, cube13
> OBJ9, ROTATION24, 1
> OBJ9, TYPE, PLATE
> OBJ9, LINR_HEAT, 3.300000E+00, 2.500000E+01

> OBJ10, NAME, SIDEX1
> OBJ10, POSITION, 0.000000E+00, 0.000000E+00, 0.000000E+00
> OBJ10, SIZE, 0.000000E+00, 4.380000E-01, 3.590000E-01
> OBJ10, CLIPART, cube13
> OBJ10, ROTATION24, 1
> OBJ10, TYPE, PLATE
> OBJ10, LINR_HEAT, 3.300000E+00, 2.500000E+01
> OBJ11, NAME, SIDEX2
> OBJ11, POSITION, 0.000000E+00, 0.000000E+00, 0.000000E+00
> OBJ11, SIZE, 0.000000E+00, 0.000000E+00, 0.000000E+00
> OBJ11, CLIPART, cube13
> OBJ11, ROTATION24, 0
> OBJ11, TYPE, PLATE
> OBJ11, LINR_HEAT, 3.300000E+00, 2.500000E+01
> OBJ12, NAME, SIDEY1
> OBJ12, POSITION, 0.000000E+00, 0.000000E+00, 0.000000E+00
> OBJ12, SIZE, 0.000000E+00, 0.000000E+00, 0.000000E+00
> OBJ12, CLIPART, cube13
> OBJ12, ROTATION24, 0
> OBJ12, TYPE, PLATE
> OBJ12, LINR_HEAT, 3.300000E+00, 2.500000E+01
> OBJ13, NAME, SIDEY2
> OBJ13, POSITION, 0.000000E+00, 0.000000E+00, 0.000000E+00
> OBJ13, SIZE, 0.000000E+00, 0.000000E+00, 0.000000E+00
> OBJ13, CLIPART, cube13
> OBJ13, ROTATION24, 0
> OBJ13, TYPE, PLATE
> OBJ13, LINR_HEAT, 3.300000E+00, 2.500000E+01
> OBJ14, NAME, TOPLAIR
> OBJ14, POSITION, 0.000000E+00, 0.000000E+00, 2.750000E-01
> OBJ14, SIZE, 0.000000E+00, 0.000000E+00, 2.750000E-01
> OBJ14, CLIPART, cubet
> OBJ14, ROTATION24, 0
> OBJ14, TYPE, BLOCKAGE
> OBJ14, MATERIAL, 2
> OBJ14, ADIABATIC, 0.000000E+00, 0.000000E+00
> OBJ14, INI_TEMP, 2.500000E+01
> OBJ14, SCAL_FIXF, 0.000000E+00
> OBJ15, NAME, TOPAIR
> OBJ15, POSITION, 0.000000E+00, 3.620000E-01, 2.750000E-01
> OBJ15, SIZE, 0.000000E+00, 3.620000E-01, 2.750000E-01
> OBJ15, CLIPART, cubet
> OBJ15, ROTATION24, 0
> OBJ15, TYPE, BLOCKAGE
> OBJ15, MATERIAL, 2
> OBJ15, ADIABATIC, 0.000000E+00, 0.000000E+00
> OBJ15, INI_TEMP, 2.500000E+01
> OBJ15, SCAL_FIXF, 0.000000E+00
> OBJ16, NAME, TOPAIR
> OBJ16, POSITION, 0.000000E+00, 7.600000E-02, 2.750000E-01
> OBJ16, SIZE, 7.600000E-02, 2.860000E-01, 9.399999E-02
> OBJ16, CLIPART, cubet
> OBJ16, ROTATION24, 1
> OBJ16, TYPE, BLOCKAGE
> OBJ16, MATERIAL, 2
> OBJ16, ADIABATIC, 0.000000E+00, 0.000000E+00
> OBJ16, INIT_TEMP, 2.500000E+01
> OBJ16, SCAL_FIXF, 0.000000E+00

> OBJ17, NAME, TOP4AIR
> OBJ17, POSITION, 3.620000E-01, 7.600000E-02, 2.750000E-01
> OBJ17, SIZE, 7.600000E-02, 2.960000E-01, 3.399999E-02
> OBJ17, CLIPART, cubet
> OBJ17, ROTATION24, 1
> OBJ17, TYPE, BLOCKAGE
> OBJ17, MATERIAL, 2
> OBJ17, ADIABATIC, 0.000000E+00, 3.000000E+00
> OBJ17, INIT_TEMP, 2.500000E+01
> OBJ17, SCAL_FIXF, 0.000000E+00

> OBJ18, NAME, AIRBOT
> OBJ18, POSITION, 1.400000E-01, 1.400000E-01, 5.100000E-02
> OBJ18, SIZE, 1.580000E-01, 1.580000E-01, 7.000000E-03
> OBJ18, CLIPART, cubet
> OBJ18, ROTATION24, 1
> OBJ18, TYPE, BLOCKAGE
> OBJ18, MATERIAL, 2
> OBJ18, ADIABATIC, 0.000000E+00, 0.000000E+00
> OBJ18, INIT_TEMP, 2.500000E+01
> OBJ18, SCAL_FIXF, 0.000000E+00
STOP
Group 11. Initialise Var/Porosity Fields
FINIT(KOND) = 6.000000E-01; FINIT(TEM1) = 2.500000E+01
No PATCHes used for this Group

INIADD = T

Group 12. Convection and diffusion adjustments
No PATCHes used for this Group

Group 13. Boundary & Special Sources
No PATCHes used for this Group

Group 14. Downstream Pressure For PARAB

Group 15. Terminate Sweeps
LSWEEP = 60
RESFAC = 1.000000E-03

Group 16. Terminate Iterations

Group 17. Relaxation

Group 18. Limits

Group 19. EARTH Calls To GROUND Station
USEGRID = T; USEGRX = T
ASAP = T

Group 20. Preliminary Printout
ECHO = T

Group 21. Print-out of Variables

Group 22. Monitor Print-Cut
IXMCON = 22; IYMON = 22; IZMON = 65
NPRMCON = 100000
NPRMNT = 1
TSWSWP = -1

Group 23. Field Print-Out & Plot Control
NPRINT = 100000
ISWPFR = 1; ISWPRL = 100000
IPROF = 3

PATCH (T1 , PROFIL, 7, 0, 0, 0, 0, 0, 1, 1)
PLT(T1 , KOND, 0.000000E+00, 0.000000E+00)
PLT(T1 , TEM1, 0.000000E+00, 0.000000E+00)

Group 24. Dumps For Restarts
NOWIPE = T
GVIEWS(P,C,5.000000E+00,-1.000000E+00,0.000000E+00)

> DOM, SIZE, 4.3800000E-01, 4.3800000E-01, 3.5900000E-01
> DOM, MONIT, 2.2650000E-01, 2.2650000E-01, 1.5510000E-01
> DOM, SCALE, 1.0000000E+00, 1.0000000E+00, 1.0000000E+00
> DOM, SNAPSIZE, 1.0000000E-02
> GRID, NSPZ_2_4, 50, 1.0000000E+00
> DOM, RELAX, 5.0000000E-01

> OBJ1, NAME, B1
> OBJ1, POSITION, 0.0000000E+00, 0.0000000E+00, 0.0000000E+00
> OBJ1, SIZE, 4.3800000E-01, 4.3800000E-01, 2.7500000E-01
> OBJ1, CLIPART, cube14
> OBJ1, ROTATION24, 1
> OBJ1, TYPE, BLOCKAGE
> OBJ1, MATERIAL, 161
> OBJ1, ADIABATIC, 0.0000000E+00, 0.0000000E+00
> OBJ1, INI_TEMP, 2.5000000E+01

> OBJ2, NAME, B2
> OBJ2, POSITION, 7.6000000E-02, 5.6000000E-02, 0.0000000E+00
> OBJ2, SIZE, 2.8600000E-01, 2.8600000E-01, 3.5900000E-01
> OBJ2, CLIPART, cube14
> OBJ2, ROTATION24, 1
> OBJ2, TYPE, BLOCKAGE
> OBJ2, MATERIAL, 162
> OBJ2, ADIABATIC, 0.0000000E+00, 0.0000000E+00
> OBJ2, INI_TEMP, 2.5000000E+01

> OBJ3, NAME, CHAR
> OBJ3, POSITION, 1.4000000E-01, 1.4000000E-01, 7.5000000E-02
> OBJ3, SIZE, 1.5800000E-01, 1.5800000E-01, 9.0000000E-02
> OBJ3, CLIPART, cube14
> OBJ3, ROTATION24, 1
> OBJ3, TYPE, BLOCKAGE
> OBJ3, MATERIAL, -1
> OBJ3, ADIABATIC, 0.0000000E+00, 0.0000000E+00
> OBJ3, INI_TEMP, 2.5000000E+01
> OBJ3, SCAL_FIXF, 0.0000000E+00
> OBJ3, INI_VEL_X_1, 0.0000000E+00
> OBJ3, INI_VEL_Y_1, 0.0000000E+00
> OBJ3, INI_VEL_Z_1, 0.0000000E+00

> OBJ4, NAME, COOLER
> OBJ4, POSITION, 1.4000000E-01, 1.4000000E-01, 5.8000000E-02
> OBJ4, SIZE, 1.5800000E-01, 1.5800000E-01, 1.7000000E-02
> OBJ4, CLIPART, cube4
> OBJ4, ROTATION24, 1
> OBJ4, TYPE, BLOCKAGE
> OBJ4, MATERIAL, 111
> OBJ4, HEAT_FLUX, 0.000000E+00, -3.140000E+01
> OBJ4, INI_TEMP, 2.500000E+01

> OBJ5, NAME, HEATER
> OBJ5, POSITION, 1.400000E-01, 1.400000E-01, 1.650000E-01
> OBJ5, SIZE, 1.580000E-01, 1.580000E-01, 1.500000E-02
> OBJ5, CLIPART, cube4
> OBJ5, ROTATION24, 1
> OBJ5, TYPE, BLOCKAGE
> OBJ5, MATERIAL, 111
> OBJ5, FIXED_TEMP, 0.000000E+00, 5.500000E+02

> OBJ6, NAME, AIR
> OBJ6, POSITION, 1.400000E-01, 1.400000E-01, 1.900000E-01
> OBJ6, SIZE, 1.580000E-01, 1.580000E-01, 7.500000E-02
> OBJ6, CLIPART, cube1
> OBJ6, ROTATION24, 1
> OBJ6, TYPE, BLOCKAGE
> OBJ6, MATERIAL, 2
> OBJ6, ADIABATIC, 0.000000E+00, 0.000000E+00
> OBJ6, INI_TEMP, 2.500000E+01
> OBJ6, SCALE_FIXF, 0.000000E+00

> OBJ7, NAME, T1
> OBJ7, POSITION, 2.190000E-01, 2.190000E-01, 7.500000E-02
> OBJ7, SIZE, 2.000000E-03, 2.000000E-03, 9.000000E-02
> OBJ7, CLIPART, default
> OBJ7, ROTATION24, 1
> OBJ7, TYPE, USER_DEFINED

> OBJ8, NAME, TOP
> OBJ8, POSITION, 0.000000E+00, 3.000000E+00, 3.590000E-01
> OBJ8, SIZE, 4.380000E-01, 4.380000E-01, 0.000000E+00
> OBJ8, CLIPART, cube13
> OBJ8, ROTATION24, 1
> OBJ8, TYPE, PLATE
> OBJ8, LINR_HEAT, 3.300000E+00, 2.500000E+01

> OBJ9, NAME, BOTTOM
> OBJ9, POSITION, 0.000000E+00, 0.000000E+00, 0.000000E+00
> OBJ9, SIZE, 4.380000E-01, 4.380000E-01, 0.000000E+00
> OBJ9, CLIPART, cube13
> OBJ9, ROTATION24, 1
> OBJ9, TYPE, PLATE
> OBJ9, LINR_HEAT, 3.300000E+00, 2.500000E+01

> OBJ10, NAME, SIDEX1
> OBJ10, POSITION, 0.000000E+00, 0.000000E+00, 0.000000E+00
> OBJ10, SIZE, 0.000000E+00, 4.380000E-01, 3.590000E-01
> OBJ10, CLIPART, cube13
> OBJ10, ROTATION24, 1
> OBJ10, TYPE, PLATE
> OBJ10,  LINR_HEAT,  3.300000E+00, 2.500000E+01
> OBJ11,  NAME,  SIDEX2
> OBJ11,  POSITION,  4.380000E-01, 0.000000E+00, 0.000000E+00
> OBJ11,  SIZE,  0.000000E+00, 4.380000E-01, 3.590000E-01
> OBJ11,  CLIPART,  cube13
> OBJ11,  TYPE,  PLATE
> OBJ12,  NAME,  SIDEY1
> OBJ12,  POSITION,  0.000000E+00, 0.000000E+00, 0.000000E+00
> OBJ12,  SIZE,  4.380000E-01, 0.000000E+00, 3.590000E-01
> OBJ12,  CLIPART,  cube13
> OBJ12,  TYPE,  PLATE
> OBJ13,  NAME,  SIDEY2
> OBJ13,  POSITION,  0.000000E+00, 4.380000E-01, 0.000000E+00
> OBJ13,  SIZE,  4.380000E-01, 0.000000E+00, 3.590000E-01
> OBJ13,  CLIPART,  cube13
> OBJ13,  TYPE,  PLATE
> OBJ14,  NAME,  TOP2AIR
> OBJ14,  POSITION,  0.000000E+00, 0.000000E+00, 2.750000E-01
> OBJ14,  SIZE,  4.380000E-01, 7.600000E-02, 8.399999E-02
> OBJ14,  CLIPART,  cube13
> OBJ14,  TYPE,  BLOCKAGE
> OBJ14,  ADIABATIC,  0.000000E+00, 0.000000E+00
> OBJ14,  INI_TEMP,  2.500000E+01
> OBJ14,  SCAL_FIXE,  0.000000E+00
> OBJ15,  NAME,  TOP3AIR
> OBJ15,  POSITION,  0.000000E+00, 3.620000E-01, 2.750000E-01
> OBJ15,  SIZE,  4.380000E-01, 7.600000E-02, 8.400000E-02
> OBJ15,  CLIPART,  cube13
> OBJ15,  TYPE,  BLOCKAGE
> OBJ15,  ADIABATIC,  0.000000E+00, 0.000000E+00
> OBJ15,  INI_TEMP,  2.500000E+01
> OBJ15,  SCAL_FIXE,  0.000000E+00
> OBJ16,  NAME,  TOP3AIR
> OBJ16,  POSITION,  0.000000E+00, 7.600000E-02, 2.750000E-01
> OBJ16,  SIZE,  7.600000E-02, 2.860000E-01, 8.399999E-02
> OBJ16,  CLIPART,  cube13
> OBJ16, ROTATION24, 1
> OBJ16, TYPE, BLOCKAGE
> OBJ16, MATERIAL, 2
> OBJ16, ADIABATIC, 0.000000E+00, 0.000000E+00
> OBJ16, INIT_TEMP, 2.500000E+01
> OBJ16, SCAL_FIXF, 0.000000E+00

> OBJ17, NAME, TOP4AIR
> OBJ17, POSITION, 3.620000E-01, 7.600000E-02, 2.750000E-01
> OBJ17, SIZE, 7.600000E-02, 2.860000E-01, 8.399999E-02
> OBJ17, CLIPART, cube
> OBJ17, ROTATION24, 1
> OBJ17, TYPE, BLOCKAGE
> OBJ17, MATERIAL, 2
> OBJ17, ADIABATIC, 0.000000E+00, 0.000000E+00
> OBJ17, INIT_TEMP, 2.500000E+01
> OBJ17, SCAL_FIXF, 0.000000E+00

> OBJ18, NAME, AIRBCT
> OBJ18, POSITION, 1.400000E-01, 1.400000E-01, 5.100000E-02
> OBJ18, SIZE, 1.580000E-01, 1.580000E-01, 7.000000E-03
> OBJ18, CLIPART, cube
> OBJ18, ROTATION24, 1
> OBJ18, TYPE, BLOCKAGE
> OBJ18, MATERIAL, 2
> OBJ18, ADIABATIC, 0.000000E+00, 0.000000E+00
> OBJ18, INIT_TEMP, 2.500000E+01
> OBJ18, SCAL_FIXF, 0.000000E+00
STOP
APPENDIX C
ERROR ANALYSIS FOR DETERMINATION OF EFFECTIVE THERMAL CONDUCTIVITY

The error associated with the measurement of the effective thermal conductivity using the procedure outlined in Chapter 3 is explained in this Appendix.

The following uncertainties existed in the measurements:

Thermocouples: ± 0.5 °C
Data Acquisition: ± 0.5 °C
Distance: ± 0.05 cm
Mass Flow Rate: ± 0.1 g/s

The absolute uncertainty was found for addition and subtraction by simply adding the individual uncertainties. For multiplication and division the sum of relative uncertainties for each quantity was calculated and then it was converted back to absolute uncertainty as shown in the following sections.

For example, for the following situation:

\[ x_1 = 4.2 \pm 0.05 \text{ cm} \]
\[ x_2 = 6.2 \pm 0.05 \text{ cm} \]
\[ T_1 = 363 \pm 1 \text{ °C} \]
\[ T_2 = 484 \pm 1 \text{ °C} \]
\[ T_{in} = 17 \pm 1 \, ^\circ C \]
\[ T_{out} = 48 \pm 1 \, ^\circ C \]
\[ m = 1.8 \pm 0.1 \, g/s \]

where \( x_1 \) and \( x_2 \) refer to location of two consecutive thermocouples. \( T_1 \) and \( T_2 \) refer to the temperature at the corresponding locations. \( T_{in} \) and \( T_{out} \) refer to water inlet and outlet temperatures, respectively, and \( m \) represents the mass flow rate of water in the cooling plate, the accumulated uncertainty is calculated as follows.

\[ Q = m \cdot C_p \Delta T \]  \hspace{1cm} (C-1)

\[ \Delta T = T_{out} - T_{in} \]  \hspace{1cm} (C-2)

\[ = (48 \pm 1) - (17 \pm 1) \]
\[ = 31 \pm 2 \]

Therefore the total heat removed by the circulating water can be calculated.

\[ Q = 1.8 \times 4.18 \times 8 \]
\[ = 60.20 \, W \]

the accumulated error in determination of \( Q \) is then found as follows:
error in $Q / Q = error in m / m + error in \Delta T / \Delta T$ \hspace{1cm} (C-3)

error in $Q = Q (error in m / m + error in \Delta T / \Delta T)$

\[= 60.20 (0.1 / 1.8 + 2 / 31)\]

\[= 7.2 \text{ W}\]

dependence the heat removed by the circulating water was $60.2 \pm 7.2 \text{ W}$.

The heat flux $q$ was calculated by dividing the heat removal rate by the cooling plate area as described in Chapter 3. The relative error was found using the above procedure.

Therefore

\[q = 0.27 \pm 0.034 \text{ W/m}^2\]

Finally the error in determination of thermal conductivity was found.

\[k_{\text{eff}} = q \Delta T / \Delta x \hspace{1cm} (C-4)\]

\[= 0.27 * (484 - 363) / (6.2 - 4.2)\]

\[= 0.45 \text{ W/m°C}\]

error in $k_{\text{eff}} = k_{\text{eff}} (error in q / q + error in \Delta T / \Delta T + error in \Delta x / \Delta x)$ \hspace{1cm} (C-5)

\[= 0.45 * (0.034 / 0.27 + 1 / 121 + 0.1 / 2)\]

\[= 0.083 \text{ W/m°C}\]

dependence

\[k_{\text{eff}} = 0.45 \pm 0.08 \text{ W/m°C}.\]