SIMULATION OF A PEBBLE BED HEAT REGENERATOR

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CERTIFICATION OF THESIS WORK

We, the undersigned, certify that **Md. Ali Ahammad Shoukat Choudhury**, candidate for the degree of **Master of Science in Engineering (Chemical)**, has presented his thesis on the subject "**Simulation of a Pebble Bed Heat Regenerator**" that the thesis is acceptable in form and content, and that the student demonstrated a satisfactory knowledge of the field covered by this thesis in the oral examination held on the 8th September,1998.

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ABSTRACT

In many industries flue gases which contain a large amount of thermal energy are released to the atmosphere at 100 to 500 ^{0}C. This project work aims to study one of the methods of recovering this wasted heat. The objectives of the project work were to develop a mathematical model for a pebble bed heat regenerator, to generate new experimental data for a cylindrical shaped packed column heat regenerator, and to compare the experimental data with the modelled results for checking the robustness of the model. A mathematical model which is applicable both for the heating and cooling cycles has been developed. Experiments were performed for five different cases. Of these, the comparisons between the modelled and experimental results are shown for two cases. The heating and cooling characteristics of the regenerator studied were very well predicted by the developed model. The deviations between the experimental and modelled results are minimum at the bottom of the column and maximum (30%) at the upper part of the column. These deviations have occurred because in the model negligible heat loss from the column wall has been assumed but in reality a large amount of heat was lost from the column wall. The optimum heating time determined for case one was three hours.

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CHAPTER I

INTRODUCTION

1.1 INTRODUCTION

The importance of energy to the economic, social, and political well-being of the countries of the world has been well documented. Energy has had a profound effect on all segments of society including the individual, as commercial organizations have developed energy management plans in order to reduce the cost of the energy which must be purchased. Energy conservation including waste heat recovery and the development of energy efficient machines and processes have resulted in considerable savings.

In many instances the availability of an energy source does not coincide timewise with the demands for energy. The development of the capability to store and retrieve energy may thus be a critical component of an energy management system or a system developed to use an alternative source of energy.

The National Research Council of the United States undertook a study on the potential of advanced energy storage system. The results of this study indicated that the ultimate decision on the installation of an energy storage system would be based on the following operating characteristics of the storage device:

1. Storage capacity
2. Storage/retrieval rate
3. Replacement lifetime

4. Weight, volume and other physical limits

5. Critical safety parameters

6. Environmental standards

7. Acceptable capital and operating costs.

The committee also noted that the areas where storage devices could be used were so varied that no specific type of device could be expected to have proper operating characteristics for all possible applications.

The physical locations of sources of energy and the device or process requiring energy seldom coincide and one must be concerned with the transport of energy from one location to another as well as the storage of energy. The ideal situation occurs when the energy transporting fluid also served as the storage medium. There are many examples of these systems. Hot water storage is used in most residential and commercial units for water service. A large number of solar units use hot water for storage. Units using a fluid as both the transport and storage media are, however, restricted to low temperature applications.

The thermal energy storage devices are those in which the storage medium and the energy transporting fluids are not the same. The storage units are thus of the indirect type in which heat is transferred from the hot fluid to the storage materials and then from the storage materials to the cold fluid stream.

As a poor developing country, Bangladesh has to raise its low per capita energy consumption and at the same time conserve its limited sources of non-renewable energy. There exists ample opportunities for improving the efficiency of natural gas utilization and many techniques exist for improving energy efficiency. Recovery of waste heat by pebble bed regenerator is one of such techniques. The present research work is an effort to develop a mathematical model for the pebble bed regenerator, to generate new experimental data, and to fit the data into a model.

1.2 OBJECTIVES OF THE PRESENT WORK

The present work studied the characteristics of a pebble bed heat regenerator. The study had the following objectives:

1) To develop a mathematical simulation model for a pebble bed heat regenerator,

2) To generate experimental data on a cylindrical shaped pebble bed, and

3) To compare experimental data with the modelled results to check the robustness of the model

The results of this study will be an addition to the literature of pebble bed heat regenerators and will be useful in designing such beds for utilization of flue gas heat in industries.

CHAPTER II

LITERATURE REVIEW

Growing concern over carbon dioxide emission implies that the industrial processes must endeavour to increase their energy efficiency. This challenge has become a very important one for existing industries. Most industries constructed before awareness of the necessity for limiting carbon dioxide emission paid little attention to energy efficiency and in particular to waste heat utilization. One of the best methods of utilization of low grade heat is to use a pebble bed heat regenerator.

Levenspiel (1984) presented preliminaries for packed bed regenerators. Packed bed regenerators are usually packed with large solids, bricks, rocks, etc. so that the pressure drop for gas flow does not become excessive and so that fine solids suspended and entrained by the gas do not plug up the unit. When hot gas enters an initially cold bed of solids a hot-temperature front of gas moves down the bed trailed by a hot front of solids, as shown in Fig. 2.1. Three phenomena lead to the spreading of these hot fronts :

- Deviation from plug flow of gas in the packed bed - some fluid moving faster, some moving slower. This behavior is characterized by the axial dispersion coefficient for the gas, **D**, a sort of diffusion coefficient.

- Film resistance to heat transfer between gas and solid. Since the particles are large the interfacial area and the heat transfer coefficient h_a can be very much lower than for beds fine solids. The term h_a characterizes this resistance.

- Resistance to heat flow into the particles. With large solids such as bricks and rocks the characteristic time for the heating of the particles can be large. The thermal diffusivity of the solids $k_s/\rho_s C_s$ characterizes this resistance.

We have three levels of analysis for fixed bed regenerators, as shown in Fig. 2.2 :

1. The flat front approximation of Fig. 2.2(a). is the simplest model. It assumes ideal plug flow of gas and immediate equalizing of gas and solid temperature. This is a crude approximation, but still useful for baseline estimates of behavior.

2. The dispersion approach of Fig. 2.2(b) describes each of the three spreading factors by a diffusion like phenomenon. This leads to a symmetrical S-shaped temperature-distance curve for solids characterized by its variance σ^2. Assuming independence of the three spreading phenomena we can add the variances to give.

$$\sigma^2_{overall} = \sigma^2_{gas\,dispersion} + \sigma^2_{film\;\;resistance} + \sigma^2_{particle\,conduction}$$

   This approach should reasonably approximate the real temperature distribution in a not-too-short regenerator.

3. The rigorous analysis which accounts properly for all three spreading phenomena should yield nonsymmetrical S-shaped curves sketched in Fig. 2.2(c). This analysis is extremely difficult and has not as yet been done.

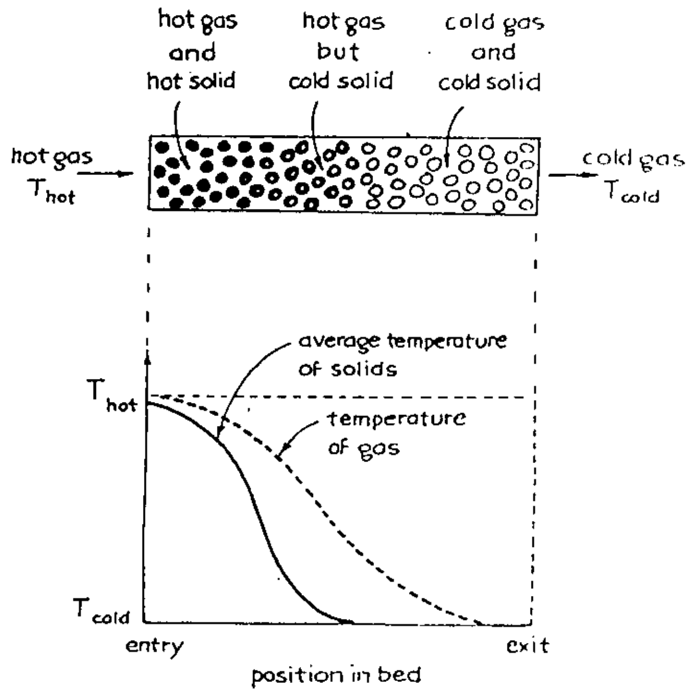


Fig. 2.1 : Advancing temperature front in gas and in solid in a packed bed regenerator.

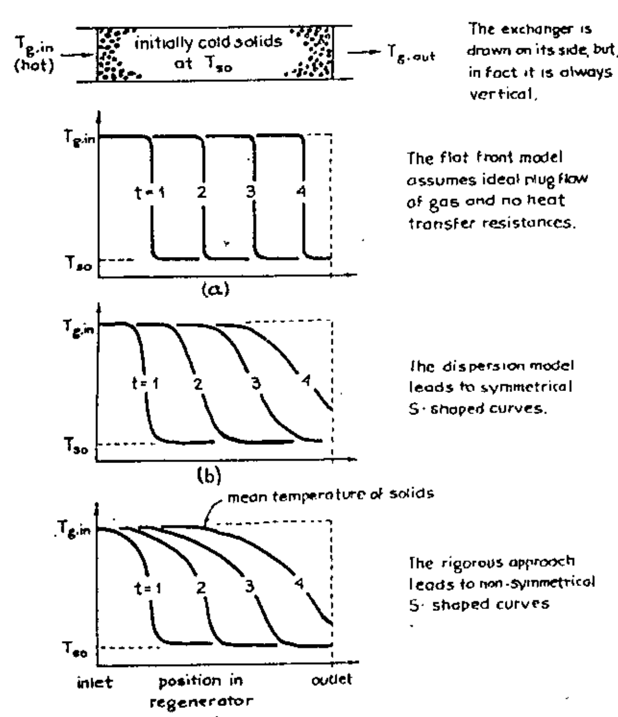


Fig. 2.2: Temperature of solids in a packed bed regenerator according to different models from the simplest to the most complicated.

Storage devices utilizing the phase change properties of the storage materials (PCM) are receiving considerable attention at the present time. Lorsch (1976) presented a set of criteria for phase change materials. In chapter III, a detail discussion about it is given.

Beasly D.E. and Ramanaryanan C. (1989) has presented a computational model of the transient thermal response of a packed bed of spheres containing a phase change material (PCM). A one dimensional separate phases formulation was used to develop a numerical analysis of the fluid temperature temporal variations. To recover stored energy from the bed the cold fluid was in reverse direction of the hot fluid. Results from the model was used for a commercial sized thermal storage bed for both the energy storage and recovery periods. Experimental measurements of transient temperature distribution in a randomly packed bed of uniform spheres containing a PCM for a step-change in inlet air temperature were reported for a range of Reynolds number. The temperature/time data were compared with numerical predictions.

Table 2.1: Bed characteristics of this experiment

Bed length	6 ft
Bed diameter	5.6 ft
Packing material	PCM encapsulated polypropylene spheres
PCM	MC 2530 paraffin wax
Particle diameter	0.5 in
Specific heat of solid	2.0 Btu/ lbm ^{0}F
Specific heat of liquid	0.5 Btu/ lbm ^{0}F
Average PCM conductivity	0.139 Btu/hr.ft.^{0}F
Mean void fraction	0.369

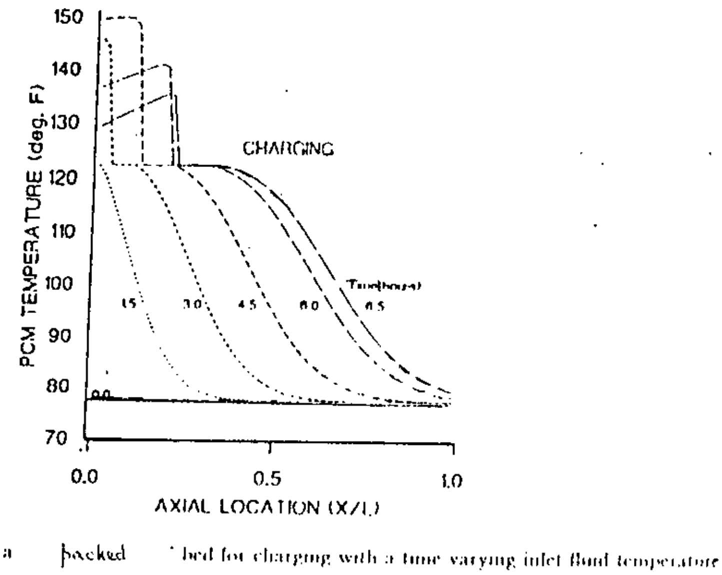


Fig. 2.3(a): Thermal response of a packed bed of spheres containing phase change materials (PCM).

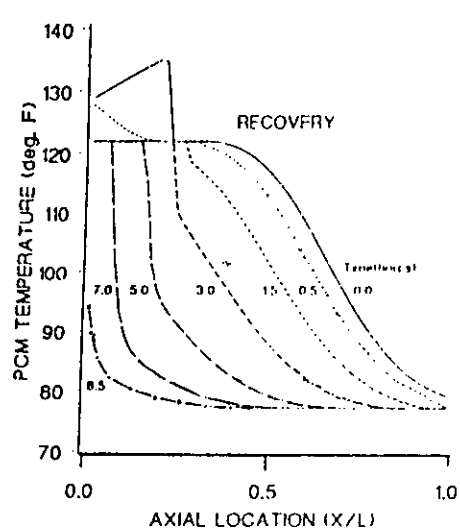


Fig. 2.3(b): PCM response in a commercial size packed bed with flow reversal and a constant inlet temperature of 77 °F

Fig. 2.3(a) and Fig. 2.3(b) illustrate the computed response of the pebble bed for a charging and recovery cycle. The bed was subjected to a time varying inlet fluid temperature which approximates the inlet fluid temperature variation during charging from a solar thermal conversion system under clear sky conditions. The inlet fluid temperature (°R) to the bed is given by

$$T_0 = 560 + 50 \sin (\pi/8)t$$

where t is in hours.

The bed was initially at a uniform temperature of 537°R and was charged for a period of 6.5 hours. At the end of the charging cycle, two thirds of the energy stored in the bed was at or above the melting temperature of the PCM. This produced an essentially constant outlet fluid temperature from the bed during recovery, with flow direction reversal.

Akter and Hossain (1993) conducted a pilot plant study to establish the design and operational parameters of the pebble bed. The experimental set-up is shown in Fig. 2.4 and consisted of a furnace, a double pipe heat exchanger, a pebble bed, two blowers and an ID fan. The dimensions of the various units are shown in the figure. The pebbles used in the pebble bed were stones of ordinary construction having an average diameter of 2.54 cm. Temperature was measured through thermocouple ports located at various points in the bed with the help of chromel-alumel thermocouples connected to digital temperature indicators. Extreme care was taken to ensure that the temperature recorded was that of the pebbles and not of the gas. The flow through the bed was measured with the help of a pitot tube inserted in the connecting pipe between the pebble bed and the ID fan.

To operate the pebble bed in the heating cycle, 132 m^3h^{-1} of natural gas was burned in the furnace. Since there was no lagging on the furnace, the flue gas temperature at the inlet of

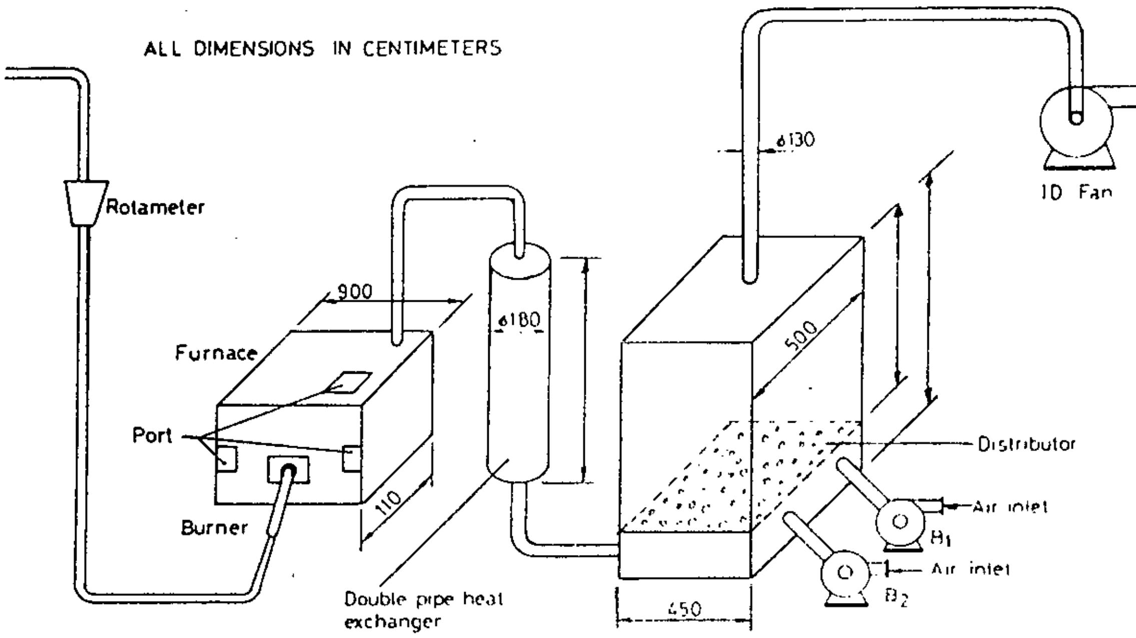


Fig. 2.4: The experimental set-up

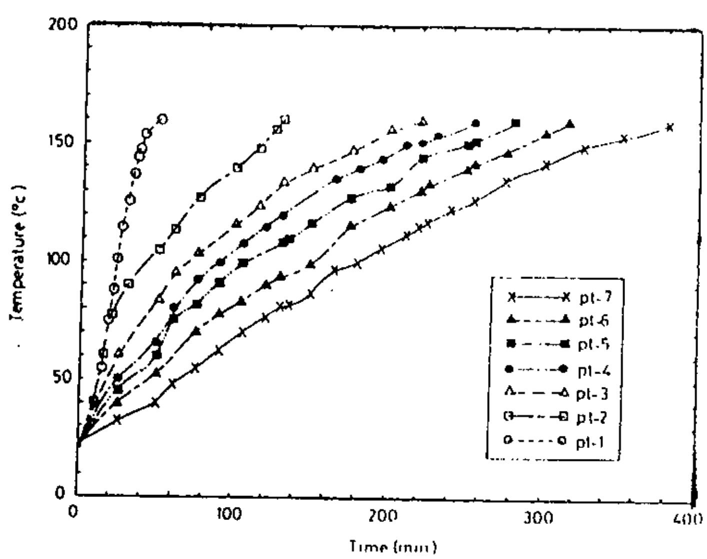


Fig. 2.5: Temperatures at various points of the bed at different times

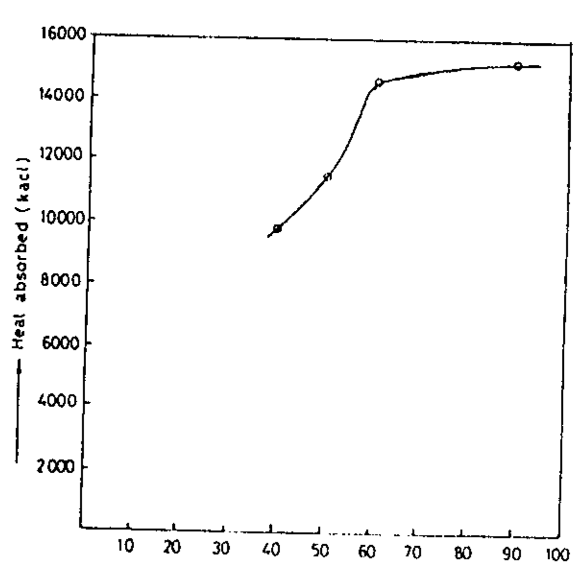


Fig. 2.6: Heat absorbed by the bed at different times

the double pipe heat exchanger was 600°C. The double pipe heat exchanger, which used tap water at ambient conditions in the annulus, was able to lower the gas temperature to approximately 300°C. The hot flue gas was allowed to mix with ambient air (supplied by the blower B_1) in the chamber below the distributor. It was found that the gas temperature at the inlet of the pebble bed was approximately 160°C. The mixing of ambient air with flue gas helped to produce a gas stream of approximately the same temperature and composition as that from the ceramic factory kilns.

Fig. 2.5 shows temperature versus time at different points in the pebble bed during a heating cycle when 567 m^3h^{-1} of gas was passed through the pebble bed. As can be seen, the heating rate slows down considerably after some time. To establish the optimum heating time, the following calculation procedure was used. The bed length was divided into ten equal sections and from Fig. 2.5 an average temperature for each section was noted. The heat absorbed in each section of the bed was calculated using a constant bed weight and specific heat. By adding the contributions of the ten sections, the total heat absorbed versus time was determined. Fig. 2.6 presents the calculated data in a plot of heat absorbed by the pebble bed against time. It is clear from the figure that continuing the heating cycle beyond 60 minutes has very little benefit. Thus, in one hour approximately 14500 kcal of heat can be absorbed in a pebble bed of dimension $0.62 \times 0.45 \times 0.45$ m = 0.126 m^3. The design of the pebble bed for the purpose of waste heat utilization was therefore based on the finding that a 0.126 m^3 pebble bed can absorb 14500 kcal of heat in one hour.

Jalalzadeh-Azar et al. (1997) made a comparison between two specific thermal energy storage materials, zirconium oxide (ZrO_2) as a sensible-heat material and a salt/ceramic composite (Na_2SO_4/SiO_2) as a phase change material, for high-temperature applications.

Second-law of thermodynamic analyses along with material stability tests are employed as criteria for the assessment of these materials. To facilitate the analysis, case studies are presented, and the thermal behaviour of the packed bed for each scenario is simulated by an experimentally validated computational model. The case studies are designed to examine the role of the heat of fusion and the material quantity in the thermal performance of the packed bed. For stability evaluation, these materials are exposed to a number of thermal cycles in a high temperature test environment. The zirconium oxide pellets not only offer excellent physical stability but prove to be thermodynamically promising as well.

CHAPTER III

THEORY OF HEAT REGENERATORS

3.1 Heat Regenerators

A heat storage device in which the heat storage and retrieval processes are repeated in a periodic fashion has been classified as a regenerator. Identical fluid passages are used during the heat storage and retrieval processes. The hot and cold fluids usually flow in opposite directions (counter flow operation), or in the same direction (co-current flow). Two types of regenerators are in common use. A rotary regenerator is a unit in which the storage material moves physically from one fluid stream to the other in a periodic fashion. A regenerator in which the storage material is stationary and a series of valves and ducts used to alternately direct the hot and cold streams through the storage material is called a fixed bed or fixed matrix regenerator. In nearly all the current applications using regenerators the hot and cold fluids are gases.

The primary function of the regenerator is to transfer heat from the hot fluid stream to the cold fluid stream in a periodic or continuous fashion. If the fluid inlet temperature and the flow rates of both fluid streams are relatively time invariant a recuperator could also be used to exchange heat between the two fluids. The major advantages of using a regenerator under these operating conditions include :

- A high heat transfer surface area per unit volume is obtainable.
- Only one set of flow channels are needed since the fluids flow through the same channels alternatively.

- An even distribution of pressure within the regenerator.
- Counterflow of the two fluid streams can give a cleaning action thereby reducing fouling.
- Vapors which are condensed during the heat retrieval process may be vaporized during the heating process and carried away with the hot fluid stream.

When the stream passing through the flow passages of the regenerator is changed, some residual fluid is left in the passages and is mixed with the incoming fluid stream. A slight decrease in the operating efficiency of the regenerator may result. If the two streams react or if the contamination of the streams is undesirable, regenerators should not be used.

Rotary regenerators are used extensively in the electric power generation industry for air preheating. A diagram of typical rotary regenerator for such an application is shown in Fig. 3.1. The hot exhaust gases leaving the furnace are used to preheat the air supplied to the furnace for combustion. Heat transfer surface area to regenerator volume ratios of over 6000 m^2/m^3 are attainable. More limited applications of rotary regenerators are for vehicular gas turbine power plants and in cryogenic refrigeration units. A major problem encountered in the design of a rotary regenerator is the sealing of the hot and cold streams from each other.

Fixed regenerators are used in the metallurgical, glassmaking, and chemical industries. A sketch of a fixed regenerator, Cowper stove, used for a blast furnace in the steel making industry is shown in Fig. 3.2. The air is preheated to a temperature of 800 - 1200°C. Regenerators used in the glass industry must be designed to withstand entrance gas temperatures of the order of 1600°C. The storage media, called checkerworks, is made of ceramic brick material.

If the hot and cold fluid streams are continuous at least two fixed bed regenerators must be used so that hot gases can pass through one regenerator while the cold gases are passing through the other regenerator. The fluid streams are then periodically switched from one regenerator to the other (see fig. 3.3).

In many applications the temperature of the cold fluid leaving the fixed bed regenerator must be maintained within a rather narrow temperature range. There are two arrangements of two or more regenerators that can be used to satisfy this operating condition. During the retrieval process in the "series-parallel" arrangement, a portion of the cold fluid is passed around the regenerator and recombined with the portion of the fluid which went through the regenerator. The amount of cold fluid which bypasses the regenerator is controlled so that the temperature of the recombined fluid stream is held at a constant value.

In the "staggered-parallel" arrangement two regenerators are connected in parallel. One operates at a "high temperature" while the other is operating at a "low temperature". The cold stream is divided with one portion of it passing through the "low temperature" regenerator and the remainder travels through the "high temperature" unit. The temperature of the recombined stream is held within the desired temperature limit by varying the flow rates of the fluid passing through the two regenerator. Once the "low temperature" regenerator has given up most of its stored energy it is removed from the system, the "high temperature" regenerator is switched to become the "low temperature" regenerator, and a fully charged regenerator is installed as a new "high temperature" regenerator. This arrangement is similar to the "series-parallel" arrangement except that the bypassed stream is heated by sending it through a partially discharged regenerator.

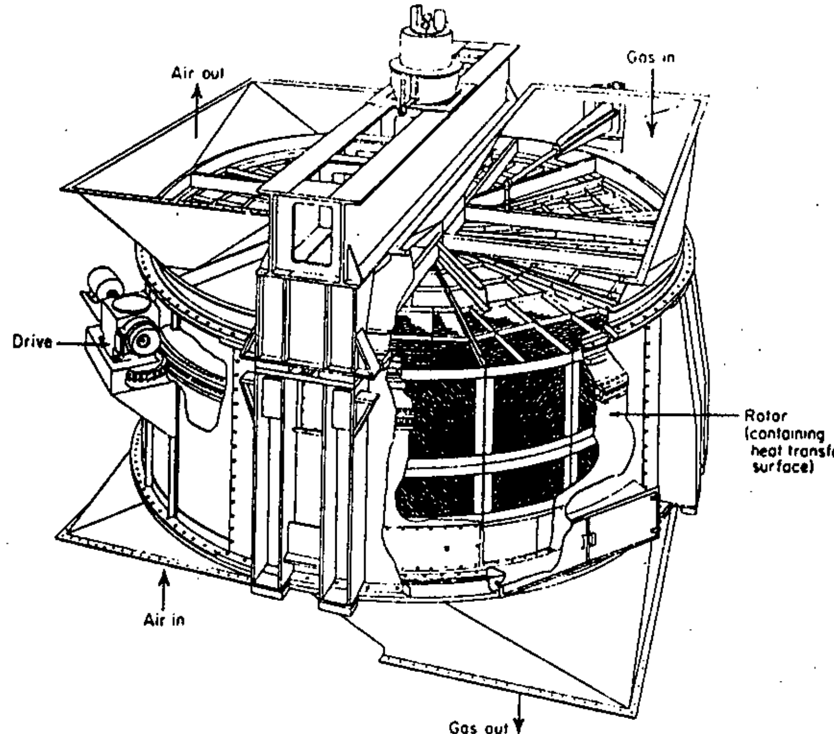


Fig. 3.1: Rotary regenerator

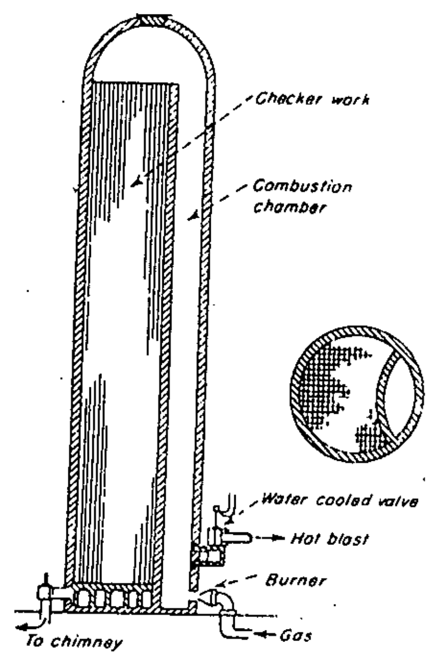


Fig. 3.2: Cowper stove regenerator

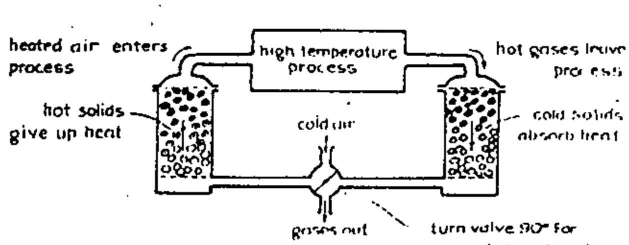


Fig. 3.3: A pair of cyclic regenerator

3.2 Thermal Storage Materials

Most thermal energy storage devices store the energy in solids and use two or more fluid streams to transport the energy between the source, the storage material, and the energy using device. There are many factors that must be taken into consideration when selecting the storage material. A set of desirable characteristics would include the following :

1. High specific heat
2. High density
3. High thermal diffusivity
4. Reversible heating and cooling
5. Chemical and geometrical stability
6. Noncombustible, noncorrosive and nontoxic
7. Low vapor pressure to reduce the cost of containment
8. Low cost for material and containment
9. Sufficient mechanical strength to support the stacking of the storage core.
10. Proper operating temperature range
11. Long operating life.

At the present time there are three major groups of heat storage media utilized for thermal energy storage. These are nonmetals, metals and phase change materials. Firebricks formed from clay, olivine, chrome, magnesite and various mixtures of these represent an important group of nonmetals used in storage devices operating at high temperatures. In an effort to obtain a material having a high volume heat capacity Feolite composed of ferric oxide, Fe_2O_3, was developed. The commercial material, called Tenemax, utilizes low cost enriched iron ores and uses virtually standard brick making manufacturing processes.

Stone is another nonmetal which is attracting considerable attention as a sensible heat storage material. Although its thermal characteristics are marginal, its cost and the fact that the unit can be fabricated on site are attractive factors. Architects are using concrete and other construction material in the design of buildings for passive storage of solar energy. The last nonmetal to be noted is small gravel. This is used primarily in packed beds for low temperature solar energy storage.

Castable metals including gray cast irons and cast irons containing alloying ingredients such as silicon and aluminium have been used in storage devices in the past. Their advantage offered by having a very high heat storage capacity per unit volume is more than offset by their high cost. As a result, most storage devices using these materials are no longer economically practical. The only exceptions are rotary regenerators which are fabricated using metallic matrices. The matrices are constructed using very thin metal strips and are designed to give a very large surface to volume ratio. The materials which is used depends to a large extent on the application. Stainless steel is used where there is a corrosive atmosphere present.

Storage devices utilizing the phase change properties of the storage material (PCM) are receiving considerable attention at the present time. The units are of interest because they have a small temperature swing as one cycles from storage to retrieval since the major portion of the energy is stored or removed while the material is at a nearly uniform temperature. The major advantage of these units, however, is that they utilize the high heat of fusion of the storage material and thus have a very high heat capacity per unit volume or weight. The mean storage temperature can be controlled to a large extent by the selection of the storage material. A set of criteria for phase change storage materials has been presented by Lorsch.

Salt hydrates have very high heats of fusion. A list of some hydrates which have been used as PCM storage materials are given in Table 3.1.

Table 3.1: List of some salt hydrates

	Chemical Compound	Melting point, °C	Heat of Fusion kJ/kg	Density Kg/m^3
Calcium chloride hexahydrate	$CaCl_2.6H_2O$	29-39	175	1630
Sodium carbonate decahydrate	$Na_2CO_3.10H_2O$	32-36	247	1440
Disodium phosphate dodecahydrate	$Na_2HPO_4.12H_2O$	36	265	1520
Sodium sulfate decahydrate	$Na_2SO_4.10H_2O$	31	251	1460
Sodium thiosulfate pentahydrate	$Na_2S_2O.5H_2O$	48	200	1670

The most promising material tested to date is sodium sulfate decahydrate ($Na_2SO_4.10H_2O$) commonly known as Glauber's salt.

Parafin waxes such as Fulfoax 33 which melts between 50-55°C and has an apparent heat of fusion of 205 kJ/kg are also attractive for certain applications. Eutectic mixtures of $NaNO_3$ or KNO_3, which have a fusion temperature of 220°C; sodium hydroxide with a fusion temperature of 315°C; lithium hydroxide, lithium hydride and lithium flouride with fusion temperature in the 1000-1700 °C range are under consideration for high temperature PCM storage systems.

3.3 Design Consideration

It has been noted that thermal energy storage devices can be used in a large variety of areas to reduce the overall energy consumption of a system; to allow for the use of an alternative source of energy; or to allow existing systems to operate continuously at or near their design point regardless of the variation of the load placed upon it. Economic justification of the use of the storage devices is necessary. One is thus concerned with obtaining an accurate assessment of the potential cost savings which would result from the use of a storage device before making the final decision. This can only be accomplished if the performance of the storage device and perhaps the complete system can be predicted accurately. Since the performance of the storage device depends on its design it becomes necessary to conduct the preliminary design of the device and the economical feasibility study together. The various items which must be considered in the design of a thermal energy storage device will now be discussed. They will, to a large extent, be dependent upon the specific application that the storage device is to be used for.

Storage material - The importance of this item in the design of a thermal energy storage device has been properly emphasized by the discussion presented in the previous section.

This item is listed only for completeness of factors which must be considered in the design of storage devices.

Pressure drop - The allowable pressure drop across the storage device will be strongly dependent on the application for which the device is intended. In many cases this is not a critical item in the design of the storage device while in other applications it represents a severe design limitation. The pressure drop is related to the properties of the fluid, the mass velocity of the fluids flowing through the channels in the storage device, the geometry of the fluid flow passages and the length of the flow channels. The magnitude of the convective heat transfer coefficient is also dependent on many of these same factors. A compromise is required since the designer ideally desires to obtain a high film coefficient and a low pressure drop. To assist him in making a decision an understanding of the influence of the convective heat transfer coefficient on the performance of the thermal storage device is required.

Configuration - The need to design a device with realistic dimensions is obvious. Special restrictions, however, are frequently imposed because of the physical location of the device or the particular system in which the storage device is to be used. The restrains usually involves the length, breadth, weight or volume of the device.

Amount of available energy stored - In many installations, particularly those involving heat storage units, the hot stream is discharged to the surroundings immediately after it leaves the storage unit. Design consideration can include the maximization of the amount of energy removed from the hot stream, however, care must be taken or an extremely long unit will result.

Utilization of storage material - This is another item which may be of considerable concern to the designer of a heat storage device. A criteria which might be used for the assessment of the performance of a storage unit could be the total amount of heat stored per unit volume of storage material. The maximum amount of heat is stored when the mean temperature of the storage material is equal to the temperature of the fluid entering the storage unit. Basing the design only on obtaining the maximum energy storage per unit volume is not recommended since during the latter part of the storage process little energy is removed from the hot fluid stream. The amount of the energy available in the hot streams which is stored is thus very small.

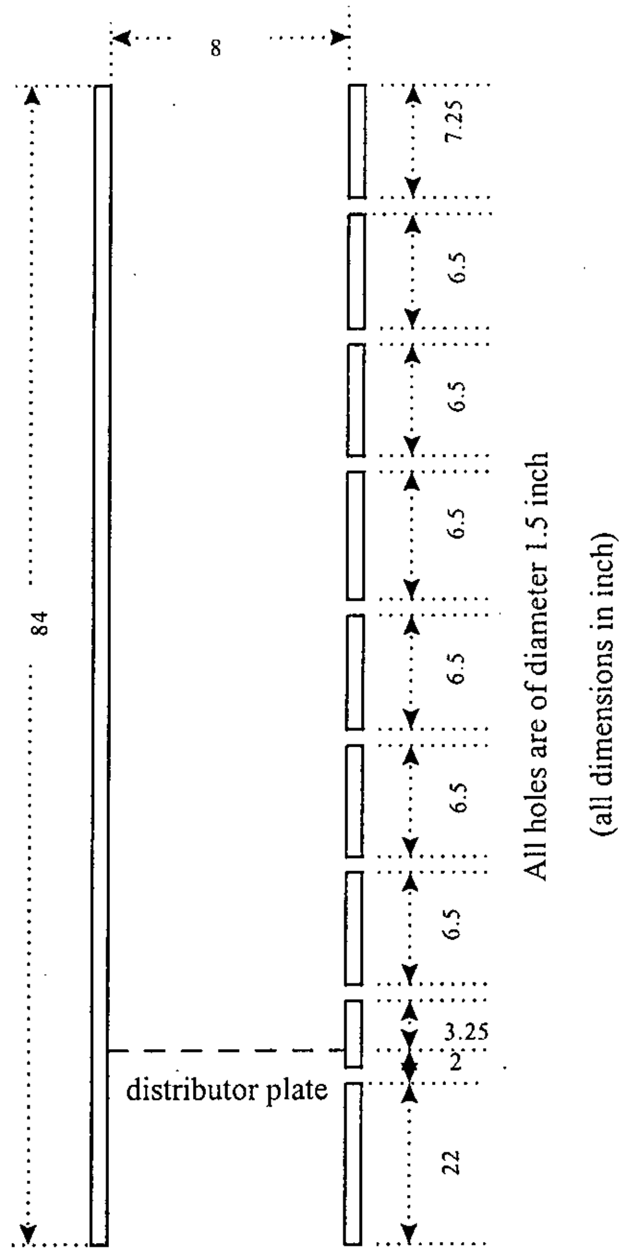
Operating characteristics - Although there are many operating characteristics which may effect the design of the storage device, most of these are contained within the parameters used to calculate the performance of the device. They in a sense act as independent variables. An operating characteristics which is of the dependent variable type is the temperature of the cold stream leaving the storage device. A minimum acceptable temperature is usually established by the device or process which uses the retrieved energy. In many systems where heat storage devices are used, it is necessary to maintain the heated fluid at a uniform temperature. Since the temperature of the cold fluid leaving a storage device during the retrieval process will decrease as the duration of retrieval increases, a combination of several storage devices or a bypass arrangement is necessary to ensure the availability of a constant temperature fluid stream.

CHAPTER IV
EXPERIMENTAL

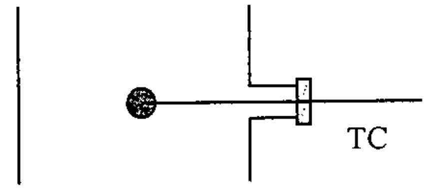
4.1 THE EXPERIMENTAL SET UP

4.1.1 PACKED COLUMN

The regenerator column used in the experiment was a mild steel pipe of inner diameter 8 inch and length 7 ft. A distributor plate was fixed two feet above the bottom of the column. The distributor plate consisted of ¼ inch holes. The center to center distance between two holes was 3/8 inch. The bottom of the column was sealed using a flange type cover having an opening at the center for air inlet. The other end of the column was open to the atmosphere. Seven holes of diameter 1.5 inch were drilled along the length of the column to insert thermocouples to measure the temperature of the bed. The distance between two consecutive holes was 8 inch center to center. Mild steel pipe sections each of length 2.5 inch and diameter 1.25 inch were fixed at the hole mouths. These pipe sections were capped with caps having small holes of diameter 1/8 inch in their center. These details are shown in Fig. 4.1.1 and Plate 1. The column was packed with pebbles of average diameter 1 inch. Care was taken so that the thermocouples do not get detached from the pebbles. Finally, the column was insulated by asbestos ropes covered with asbestos powder paste. The thickness of insulation was 0.75 inch.



The Packed Column



Thermocouple fixed to the stone

Fig. 4.1.1 : The Packed Column

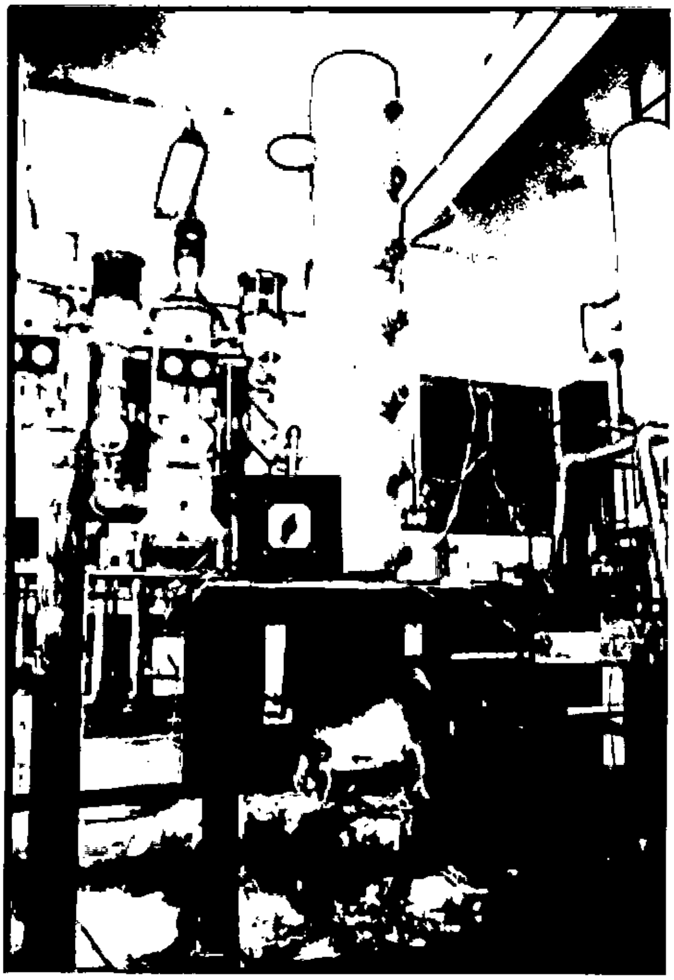


Plate 1: The packed column

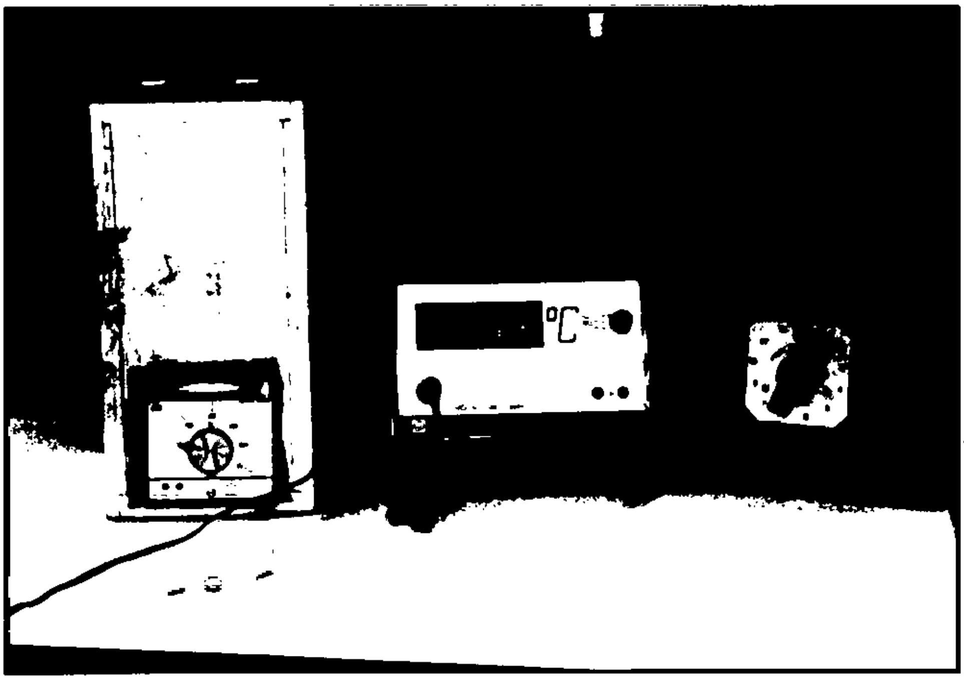


Plate 2: The digital temperature indicator and temperature controller.

4.1.2 TEMPERATURE MEASUREMENT

The thermocouples used were made up from thermocouple wires by fusing the metallic tips. All the thermocouples were tested in boiling water to ensure that the readings were 100 ^{0}C. To measure the stone temperatures accurately the thermocouples were fixed to the center of the stones using a resin glue (ARALDITE) by first drilling a hole to the center of the stone. The drilling proved to be a very difficult task because the usual drill-bits got eroded due to extreme friction. Later diamond drill-bits had to be used. The diameter of the holes in the stones were 1/8 inch and the length approximately ½ inch. The thermocouples with the stones fixed on their ends were tested again in boiling water to ensure that these have retained their calibrations. It was found that all the thermocouples with the fixed stones gave the correct boiling water temperature. Only one digital temperature indicator was used in measuring the temperatures. All the thermocouples were connected to the digital temperature indicator through a selector (see Plate 2).

4.1.3 HEATER AND TEMPERATURE CONTROLLER

To get an air stream of the desired temperature, a 4 feet pipe of diameter 2 inches was placed in a tubular furnace (see Plate 3). The pipe was packed with berl saddles in order to increase the residence time of the flowing air and to ensure good contact with the pipe wall. The temperature of the air at the outlet of the furnace was measured before passing it into the column. The temperature of the entering air was controlled by an on-off controller.

Plate 3: The heater and the controller.

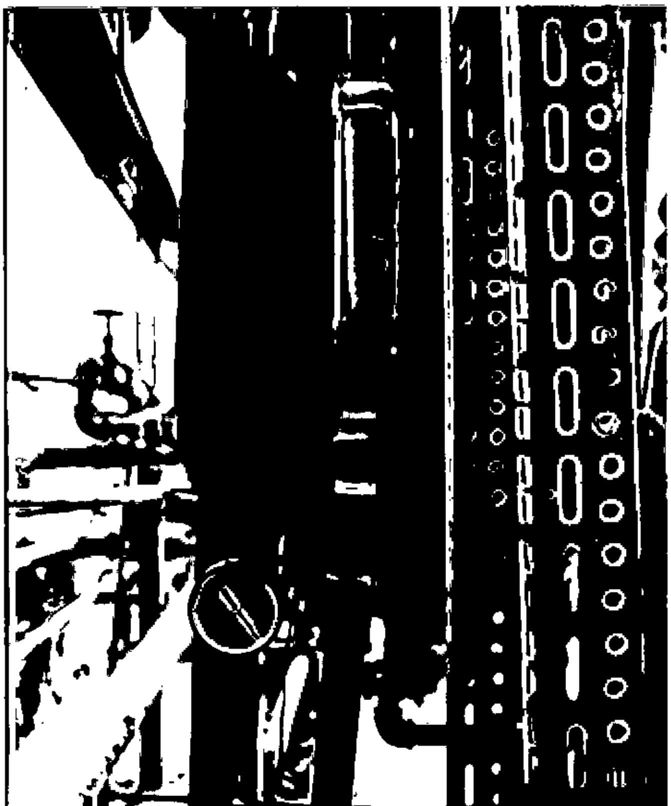


Plate 4: The Rotameter.

4.1.4 COMPRESSOR FOR AIR SUPPLY

The laboratory compressor was used to supply the air required for the experiment. Unfortunately, the capacity of the compressor was not sufficient to provide the air supply requirement for all the experiment designed. It was only able to supply a maximum of 400- 480 litres/min of air. The pressure range of the compressor was 30 - 60 psig.

4.1.5 AIR FLOW MEASUREMENT

The flow rate of the air was measured by an air-rotameter supplier calibrated in the range 0 - 600 to measure the air flow rate in litre/min at standard conditions (Plate 4). The air measurement was performed at a point prior to entry into the furnace.

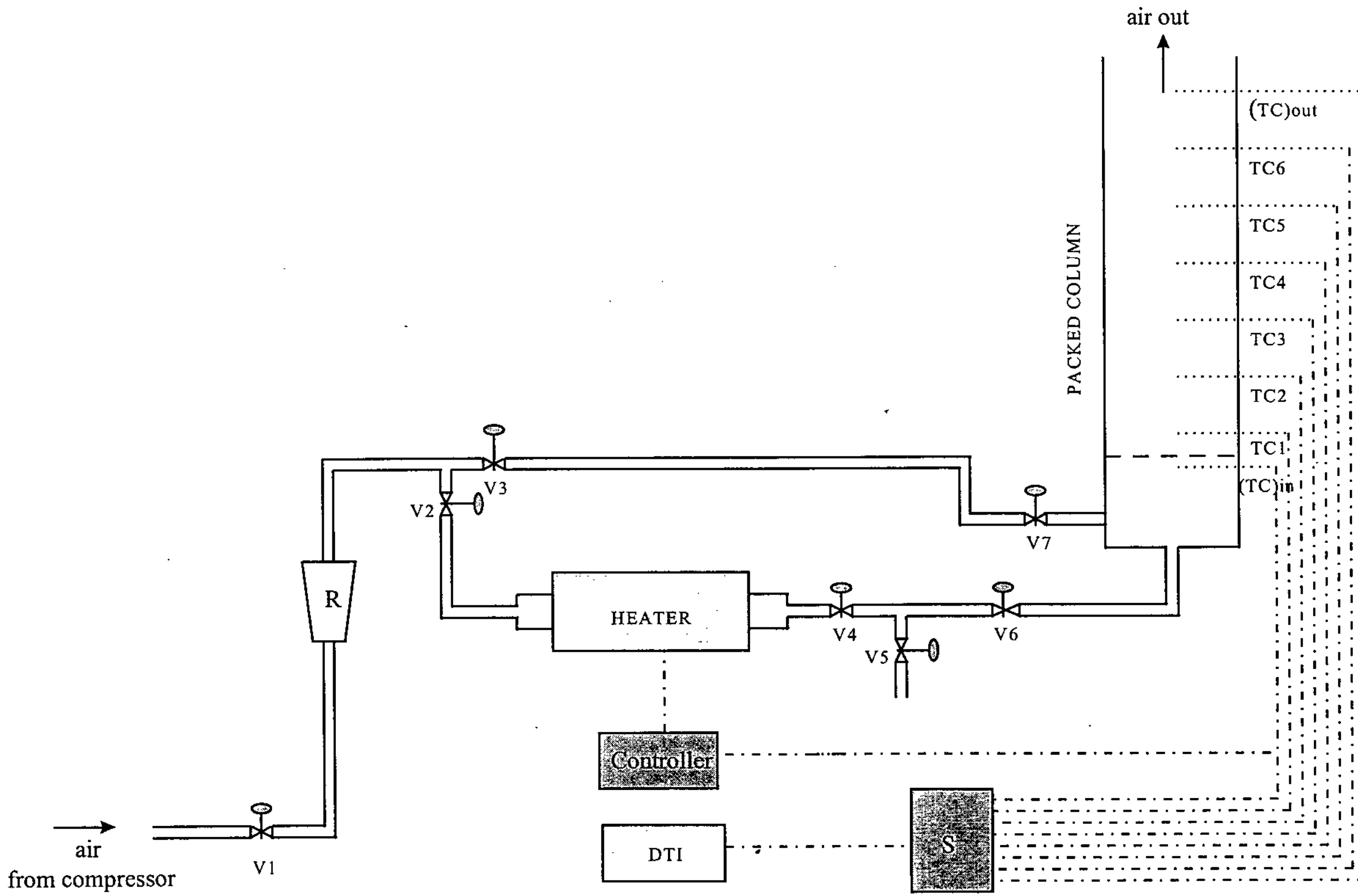


Fig. 4.2.1 : Experimental Setup

4.2 : EXPERIMENTAL PROCEDURE

The experiment consisted of two cycles : 1) Heating Cycle, and 2) Cooling Cycle.

1) **Heating Cycle :** At the beginning of the experiment, the furnace was heated up for 10 minutes and the compressor was allowed to attain its maximum pressure, 60 psig. The experimental set up is shown in Fig. 4.2.1. The valves V2, V4, V6 were opened and V7 was kept closed. The air was allowed to pass through the heater by controlling the valve V1, and was measured using the rotameter, R. To control the temperature of the air fed into the column, temperature measurement was performed at the point $(TC)_{in}$ as shown in Fig. 4.1.1. The bed was heated up gradually as the hot air passes up the column. The temperatures at different points in the column was measured by using the thermocouples, TC1, TC2, etc. All thermocouples were connected to the digital temperature indicator, DTI, through the selector, S. The temperatures at different points in the bed, and the inlet and outlet air temperatures were recorded at 10 minutes interval.

2) **Cooling Cycle :** At the end of the heating cycle, the valves V2, V4, and V6 were closed, and V3 and V7 were opened. The cooling air was also supplied from the compressor and measured by the rotameter, R. As the air moved up through the bed, it absorbed heat from the pebbles and cooled the bed. As in the heating cycle, the temperatures at different locations in the bed, and the inlet and outlet air temperatures were measured and recorded at 10 minutes interval.

CHAPTER V

MODELLING OF THE HEAT REGENERATOR

In an effort to simulate the performance of a packed bed heat regenerator, a model was developed. The model is essentially the conservation of energy equations for the fluid stream and the storage material. The storage material is stationary while the fluid stream (air) passes through the porous packed bed. The model thus treats the two phases separately with only a heat exchange interaction, which takes place through the pebble surfaces. The parameter, a, surface area of the pebbles per unit volume of the column, is the heat exchange surface between the fluid and solid in each section. This implies that in each section there is a solid mass whose temperature is changed by heat transfer from the fluid through the total surface area available in that section calculated from the pebble surface areas. The packed bed is assumed to be divided into several sections of equal height and each section behaves as a complete mixing cell, i.e., the temperature is same in all parts of the section. The temperature measured at the center of a section by means of a thermocouple with a pebble fixed at its end (see Fig. 4.1.1) is the representative temperature of that section.

5.1 DERIVATION OF THE MODEL EQUATIONS

In the derivation of the model the following assumptions are used :

1. Thermal properties of both air and stones are constant.
2. Radial temperature gradient within a given stone is neglected.

3. Transfer of heat by sphere-to-sphere contact or by conduction within air is neglected.

4. Air properties (velocity, density, temperature, etc.) are not a function of radial position.

5. Pressure drop in the column is negligible.

6. Change in mass hold-up of air in any section is neglected.

7. No heat loss from the walls of the column.

Model :

The column height is divided into a number of equally spaced intervals, each of length ΔZ, as shown in Fig. 5.1. Consider the volume enclosed by the m and m+1 planes at time Δt.

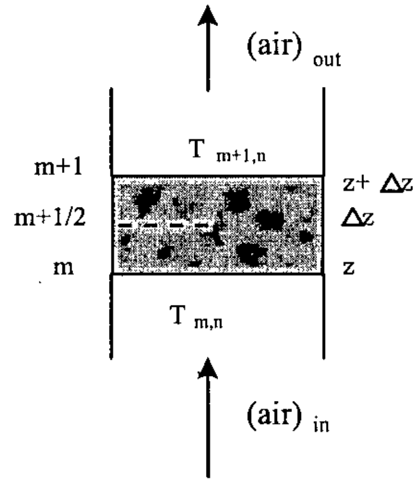


Fig. 5.1: Differential element for energy balance

A finite energy balance is written on the air contained in the volume.

Heat of gas in at z = heat absorbed by the stones + heat of gas at (z + Δz).

$$M_{m,n} C_a T_{m,n} = h(S \Delta Z a)\left(T_{m+\frac{1}{2},n} - \theta_{m+\frac{1}{2},n}\right) + M_{m+1,n} C_a T_{m+1,n} \tag{1}$$

If the change in the air holdup is neglected

$$M_{m,n} = M_{m+1,n} = M_a \, (Let)$$

Again, $$T_{m+1/2,n} = (T_{m,n} + T_{m+1,n})/2$$

Substituting into eq.(1), we get

$$M_a C_a (T_{m,n} - T_{m+1,n}) = h(S\Delta Za)\left(T_{m+1,n} + T_{m,n}\right)/2 - \theta_{m+\frac{1}{2},n}\right)$$

or, $$(T_{m,n} - T_{m+1,n}) = \frac{h(S\Delta Za)}{M_a C_a}\left(T_{m+1,n} + T_{m,n}\right)/2 - \theta_{m+\frac{1}{2},n}\right)$$

or, $$(T_{m,n} - T_{m+1,n}) = \frac{1}{2M}\left(T_{m+1,n} + T_{m,n}\right) - 2\theta_{m+\frac{1}{2},n}\right)$$

where, $$M = \frac{M_a C_a}{h(S\Delta Za)} = \frac{\textit{heat capacity of air}}{\textit{heat transferred to the pebbles}}$$

or, $$T_{m+1,n} = \frac{2M-1}{2M+1} T_{m,n} + \frac{2}{2M+1} \theta_{m+1/2,n} \tag{2}$$

or, $$T_{m+1,n} = A \; T_{m,n} + B \, \theta_{m+1/2,n} \tag{3}$$

where, $$A = \frac{2M-1}{2M+1}, \quad B = \frac{2}{2M+1}$$

Examination of equation (2) discloses that a negative effect of $T_{m,n}$ on $T_{m+1,n}$ can be avoided if $M > 1/2$.

Again a finite energy balance on both the air and stones contained in the differential volume gives :

heat lost by the air during time Δt = heat taken by the stones during time Δt

or, $$M_a \, C_a \, (T_{m,n} - T_{m+1,n}) \, \Delta t = W_s \, C_s \, (\theta_{m+1/2,n+1} - \theta_{m+1/2,n})$$

or, $$T_{m,n} - T_{m+1,n} = \frac{W_s C_s}{M_a C_a \Delta t}(\theta_{m+1/2,n+1} - \theta_{m+1/2,n})$$

or, $$T_{m,n} - T_{m+1,n} = N(\theta_{m+1/2,n+1} - \theta_{m+1/2,n})$$

where, $$N = \frac{W_s C_s}{M_a C_a \Delta t} = \frac{\textit{heat capacity of the pebbles}}{\textit{heat capacity of air}},$$

and $W_s = S\Delta Z(1-\varepsilon)\rho_s$

or, $$\theta_{m+1/2,n+1} = \theta_{m+1/2,n} + \frac{1}{N}(T_{m,n} - T_{m+1,n}) \quad (4)$$

Substituting the expression of $T_{m+1,n}$ from equation (2) into the equation (4),

$$\theta_{m+1/2,n+1} = \theta_{m+1/2,n} + \frac{1}{N}T_{m,n} - \frac{1}{N}\left(\frac{2M-1}{2M+1}T_{m,n} + \frac{2}{1+2M}\theta_{m+1/2,n}\right)$$

or, $$\theta_{m+1/2,n+1} = \frac{N(2M+1)-2}{N(2M+1)}\theta_{m+1/2,n} + \frac{2}{N(2M+1)}T_{m,n}$$

or, $$\theta_{m+1/2,n+1} = C\theta_{m+1/2,n} + D\,T_{m,n} \quad (5)$$

where, $$C = \frac{N(2M+1)-2}{N(2M+1)}, \qquad D = \frac{2}{N(2M+1)}$$

Examination of equation (5) shows that the negative effect of $\theta_{m+1/2,n}$ on $\theta_{m+1/2,n+1}$ can be avoided if

$$N > \frac{2}{2M+1}$$

Now, equations (3) and (5) will be used to calculate the temperatures of the stones and air at different positions of the bed at different times.

5.2 ALGORITHM FOR COMPUTER SOLUTION

1. The column height is divided into a number of equally spaced intervals, each of length ΔZ

2. Read the values of the variables : D_i, Δt, ΔZ , D_p, ρ_s, C_s, ε, air flowrate, ρ_{air}, Cp_{air}, and h_i

3. Supply the values of TA(m,n) at m = 0 and n = 0, 1, 2, … …,12. where, TA = air temperatures, m = distance increment, n = time increment.

4. Provide the values of TP (m,n) at n=0, m=0, 1, 2, … … … 11, where, TP = θ = pebble temperatures of the different sections of the bed.

5. Calculate the constants of the equations (3) and (5)

6. For air, we assume that m=0 is the position just below the distributor plate.

   For pebble bed we assume that m+1/2 = m = 0 is the center of the first differential section of the bed. m+1/2 = m is assumed to avoid complicacy.

7. From the known values of inlet air temperatures and the initial temperatures of the various sections of the bed, the temperatures of the air entering into the various sections of the bed for the first time interval can be calculated using equation (3).

8. From the calculated entering air temperatures and the initial temperatures of the various sections of the bed, the temperatures of the different sections of the bed for the first time interval can be obtained from equation (5).

9. Repeating steps 7 and 8 , the temperatures of the air and the different sections of the bed for the other time intervals can be calculated.

The FORTRAN program is given in Appendix-2.

CHAPTER VI

RESULTS AND DISCUSSIONS

Experiments were performed to study the heating and cooling cycles. The experimental set-up and procedure are described in chapter IV. The different experiments performed consisting of heating and cooling cycles are designated by case numbers. In all, five cases have been studied. Following the presentation of the experimental work, the modelling work is presented. First, the modelled results of two of the cases are presented. After this, the modelled results of these two cases are compared with the experimental results. At the very end, in this chapter, the heat absorbed by the bed at different times for case 1 is presented.

The results are presented in the form of temperature vs. time curves. It is to be noted that the first and the last curves are the temperatures of the inlet and outlet air. The curves between these two lines are the temperatures of the solids in the respective section of the bed.

6.1.1 Case 1 : 5 ½ hours Heating and 2½ hours Cooling

The objective of this particular experiment was to study the cooling cycle after raising the entire bed to some constant value. However, this could not be achieved due to the facts that the heat loss from the column was very high and the air supply compressor could not be operated more than eight hours at a stretch. The experimental data are shown in Appendix-1 (Tables 8.1.1(a) and 8.1.1(b)). The average air flow rate was 352 litres/min and the average inlet hot air temperature was 185 ^{0}C. As can be seen from Fig. 6.1.1(a), the temperatures of the first three sections of the bed became constant after 5½ hours heating (132 ^{0}C, 114^{0}C , 105 ^{0}C, respectively). The cooling of the bed was started after the five and a half hours of the heating cycle. During cooling, the average air flow rate was 358 litres/min and the average inlet air temperature was 51^{0}C. The reason why the inlet air temperature is so high is that the cooling air had to pass through a portion of the pipeline and a portion of the column below the distributor plate which have been heated up during the heating cycle before entering into the bed. The cooling characteristics of the bed are shown in Fig. 6.1.1(b). From this figure, we can see that the first three sections were cooled during the cooling cycle, but the other sections were slightly heated first and then cooled. This phenomena is more pronounced in Fig. 6.1.2(b). This is because the air was heated to a temperature higher than that of the upper sections of the bed. In fact, during the experiment, the last two sections of the bed were cooled very little.

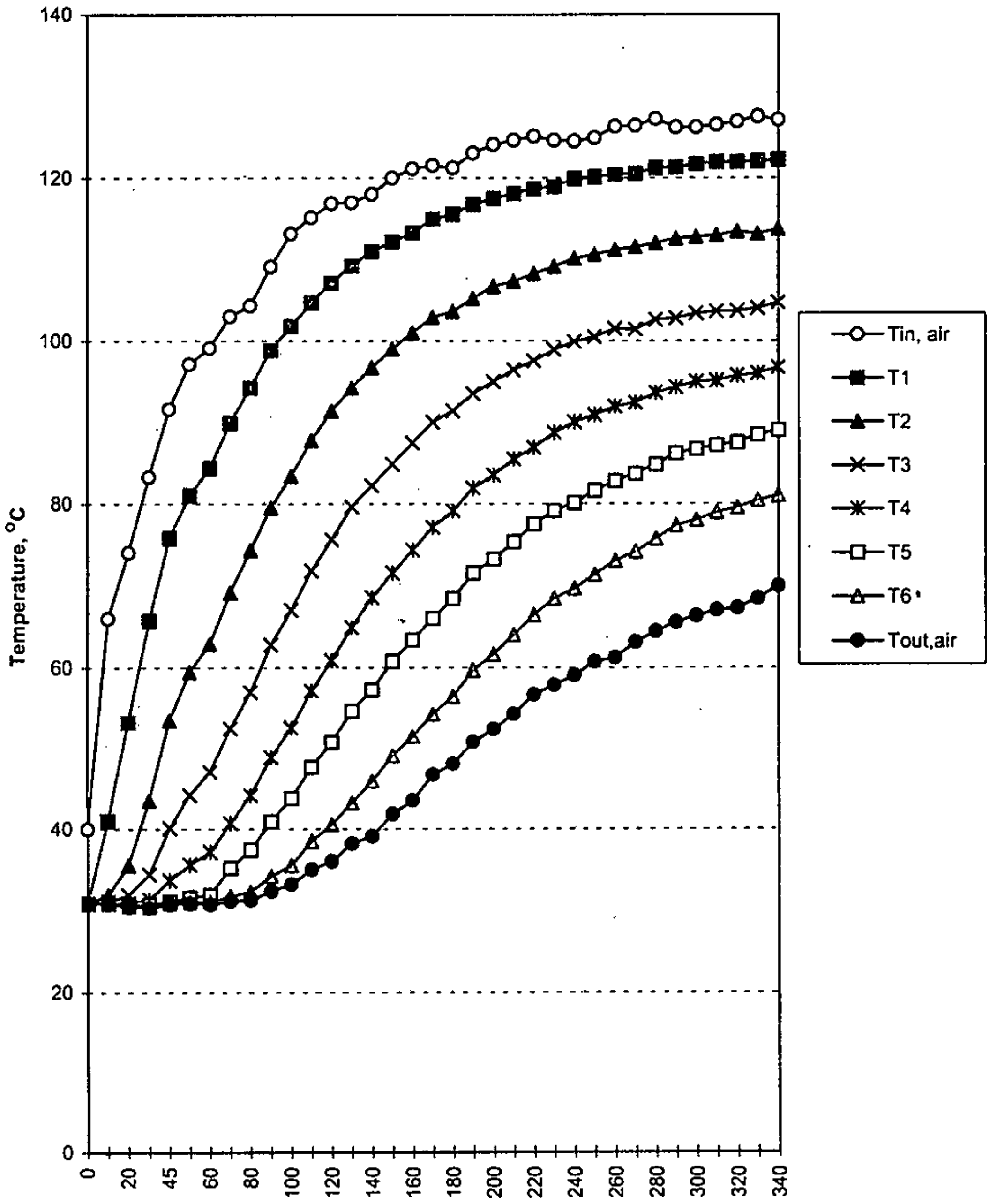


Fig. 6.1.1(a) : Experimental Temperature vs. Time curves for heating (Case 1: 5.5 hrs heating and 2.5 hrs cooling)

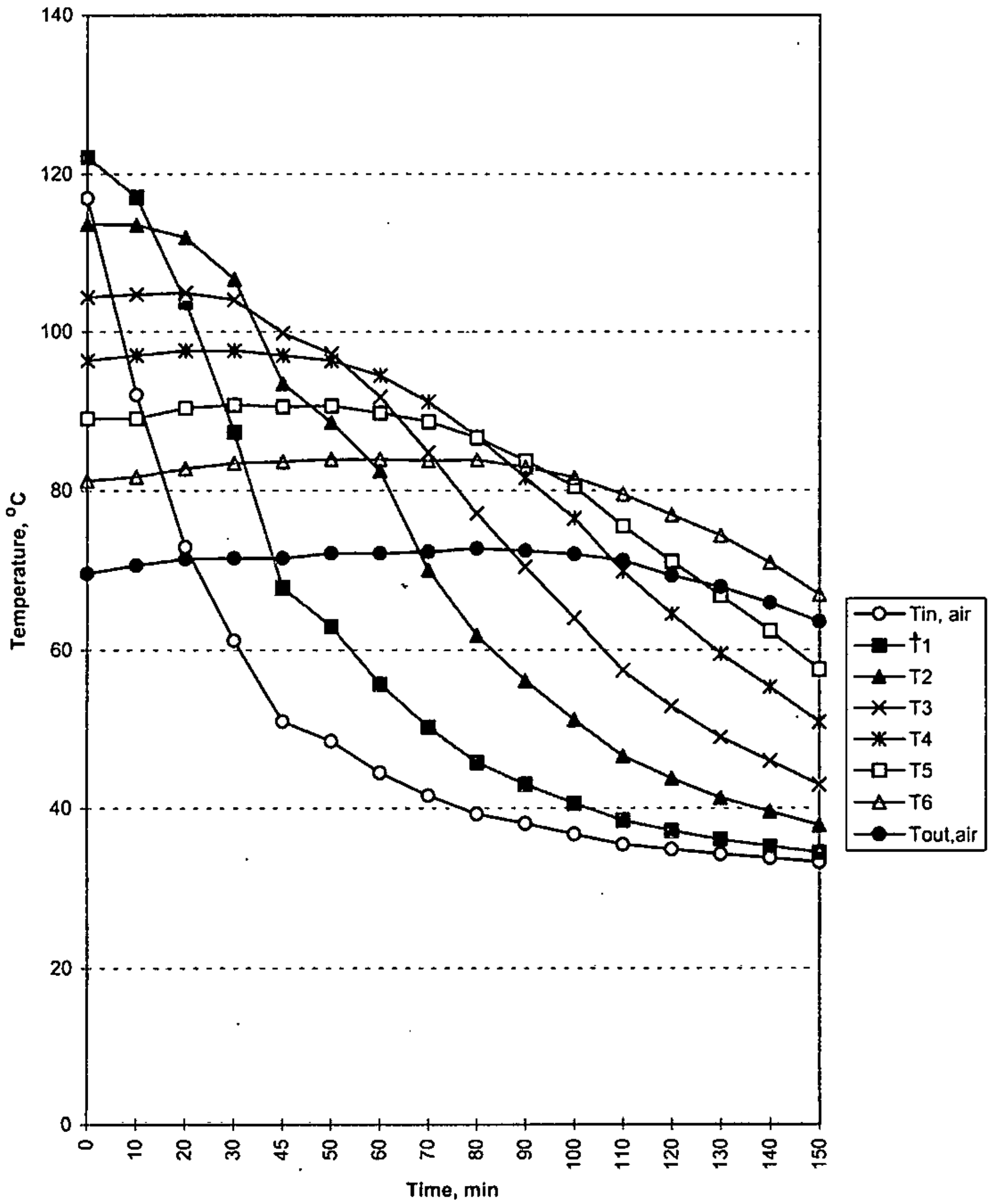


Fig. 6.1.1(b) : Experimental Temperature vs. Time curves for cooling (Case 1: 5.5 hrs heating and 2.5 hrs cooling)

6.1.2 Case 2 : 3 hours Heating and 2½ hours Cooling

This experiment was performed to compare the characteristics of heating and cooling curves with that of case 1. Here the heating time was reduced, but the cooling time was unchanged. The experimental data are shown in Appendix-1 (Table 8.1.2(a) and 8.1.2(b)). During heating the average air flow rate was 385 litres/min and the average temperature of the inlet hot air was 175 ^{0}C. From Fig. 6.1.2(a), it can be seen that the temperatures of the first two sections have been constant (185 ^{0}C and 170 ^{0}C) after three hours heating. The cooling characteristics of the bed are shown in Fig. 6.1.2(b). During cooling the first two sections were cooled down throughout the experiment but the other sections were first heated and then cooled. During cooling of the bed, the air got heated up gradually as it passed up through the bed. When the air had passed out of the first two sections of the bed, its temperature was higher than that of the upper sections. Under this condition, the upper sections (3, 4, 5, & 6) absorbed heat instead of releasing heat. This caused the temperatures of these sections to increase. After a certain time, the first two sections of the bed had cooled down and were no longer able to heat the air to a temperature higher than that of the sections 3, 4, 5 or 6. From then onwards, the top sections started releasing heat. The further the section from the distributor plate, the longer it took to start releasing heat. Since the cooling cycle was of short duration, the last two sections were cooled very little. This behaviour is identical to the previous case.

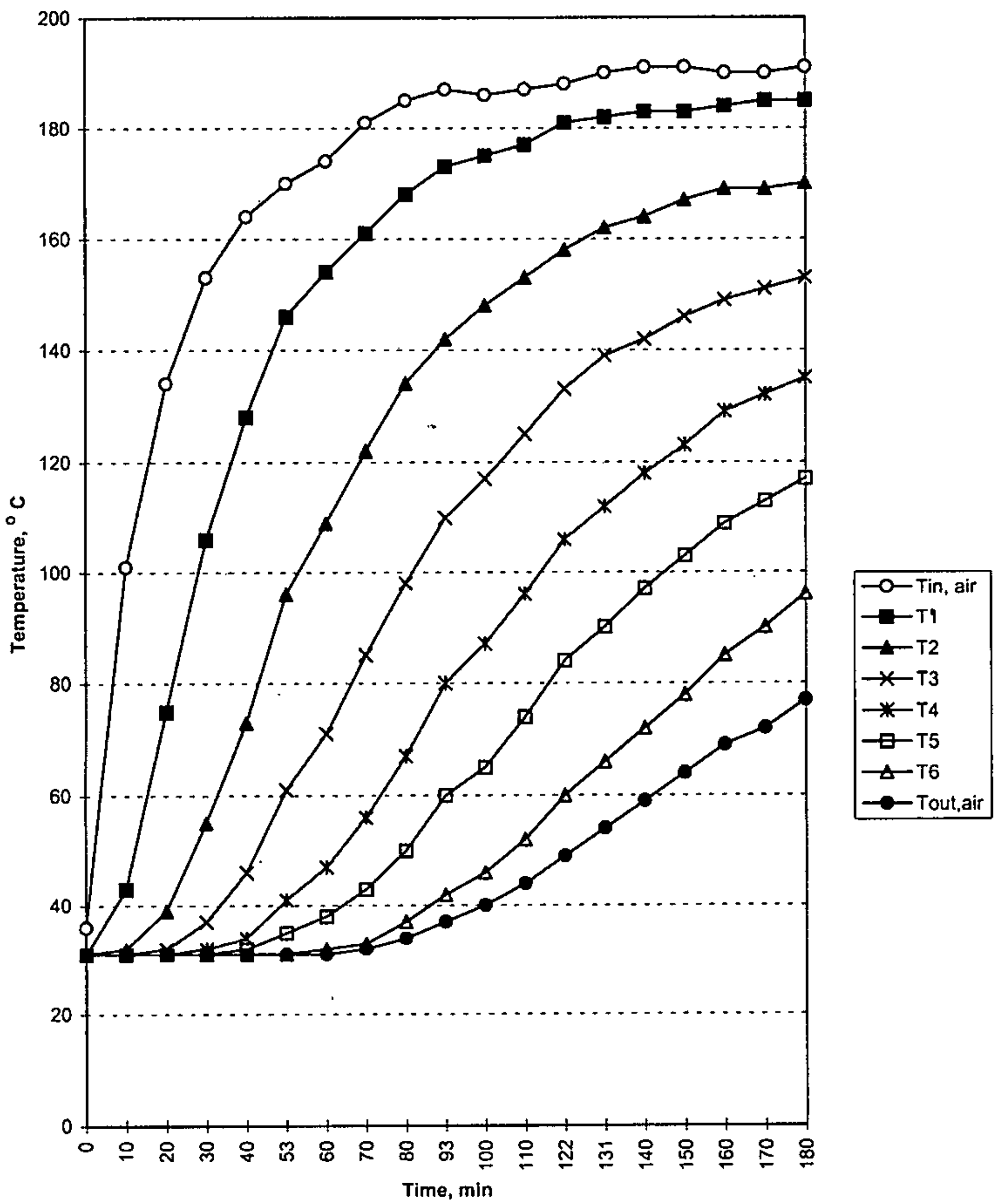


Fig. 6.1.2(a): Experimetnal Temperature vs. Time curves for heating (Case 2: 3 hours heating and 2.5 hours cooling)

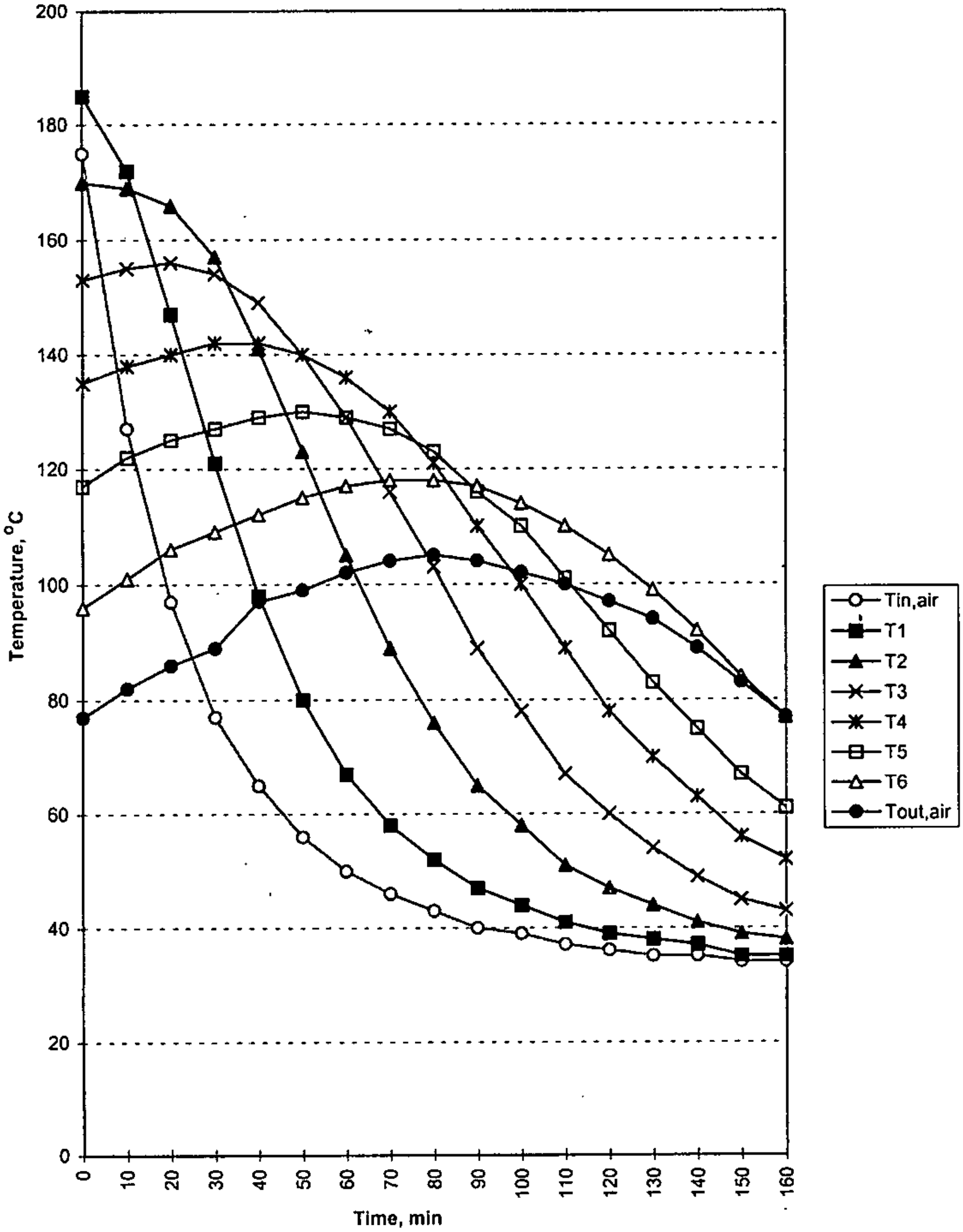


Fig. 6.1.2(b) : Experimental Temperature vs. Time curves for cooling (Case 2: 3 hours heating and 2.5 hours cooling)

6.1.3 Case 3 : Two Cycles of 1 hour Heating and 1 hour Cooling

This experiment consisted of two cycles of one hour heating and one hour cooling. The experimental data are shown in Appendix-1 (Table 8.1.3(a), 8.1.3(b), 8.1.3(c), and 8.1.3(d)). As shown in Fig. 6.1.3(a), during the first hour of the heating cycle, the temperatures of all sections of the bed were increasing and had not attained a constant temperature. This clearly indicates that the optimum heating cycle would be greater than one hour. After one hour of heating, the cooling cycle was started. As shown in Fig. 6.1.3(b), only the first section of the bed was releasing heat to the air. The other sections were absorbing heat from the air heated up in the first section. So the temperatures of these sections were increasing instead of decreasing. This phenomena has been discussed for case 1 and 2.

An interesting phenomena was observed during the second heating cycle. As can be seen from the Fig. 6.1.3(c), the first section of the bed got heated just like in the first cycle, but the other sections were cooled first and then heated. The reason is that the cooling cycle being of one hour duration only did not allow sufficient heat to be extracted from the bed. During the first hour of cooling, the first section was cooled down to a temperature of 54 ^{0}C. When the hot air passed through this section during the second hour of heating, most of the heat was used up to heat this section and the temperature of the air was decreased to a value lower than that of sections 2, or 3. Therefore, these two sections experienced cooling instead of heating. As soon as the air passed out of section 3, it was heated to a temperature higher than that of sections 4, 5, or 6. These sections, therefore, experienced both heating and cooling during the second heating cycle. The behaviour described are shown in Fig. 6.1.3(c). During the second hour cooling, only the first section was cooled throughout while the others were heated first and then cooled but very little. As can be seen from Fig. 6.1.3(d), the air from the first section of the bed was heated to a temperature higher than that of other sections. After 20 minutes, the first section of the bed had cooled down to a temperature lower than that of the second section. The second section started to cool after this period. This phenomena progressed up the bed, i.e., the third section started cooling when its temperature was higher than that of the second section. The temperature curves for the second cooling cycle are shown in Fig. 6.1.3(d). Since the purpose of a heat regenerator is to recover heat, this case did not prove to be an efficient one.

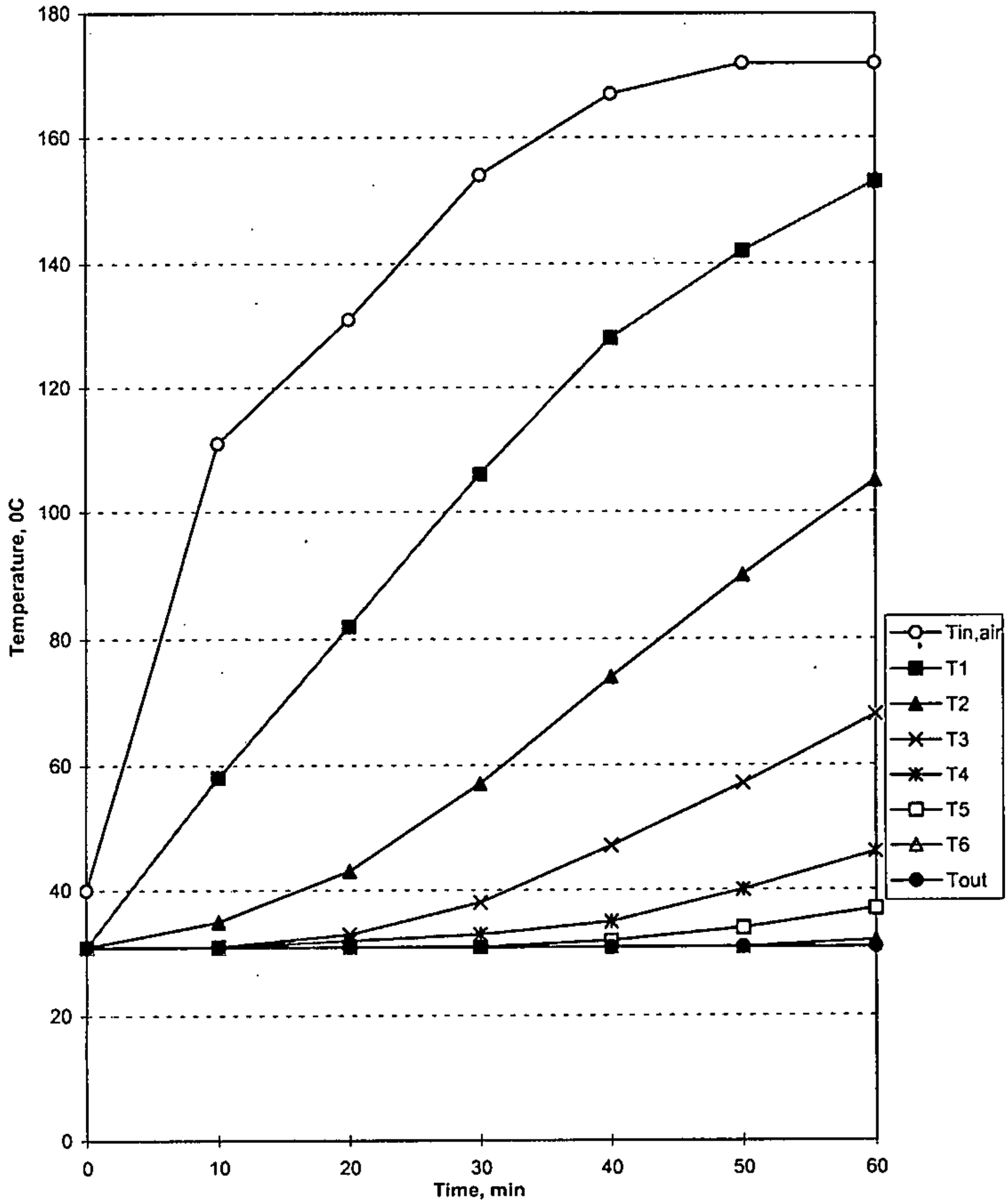


Fig. 6.1.3(a): Experimetnal Temperature vs. Time curves for first hour heating (Case 3: Two cycles of 1 hr heating and 1 hr cooling)

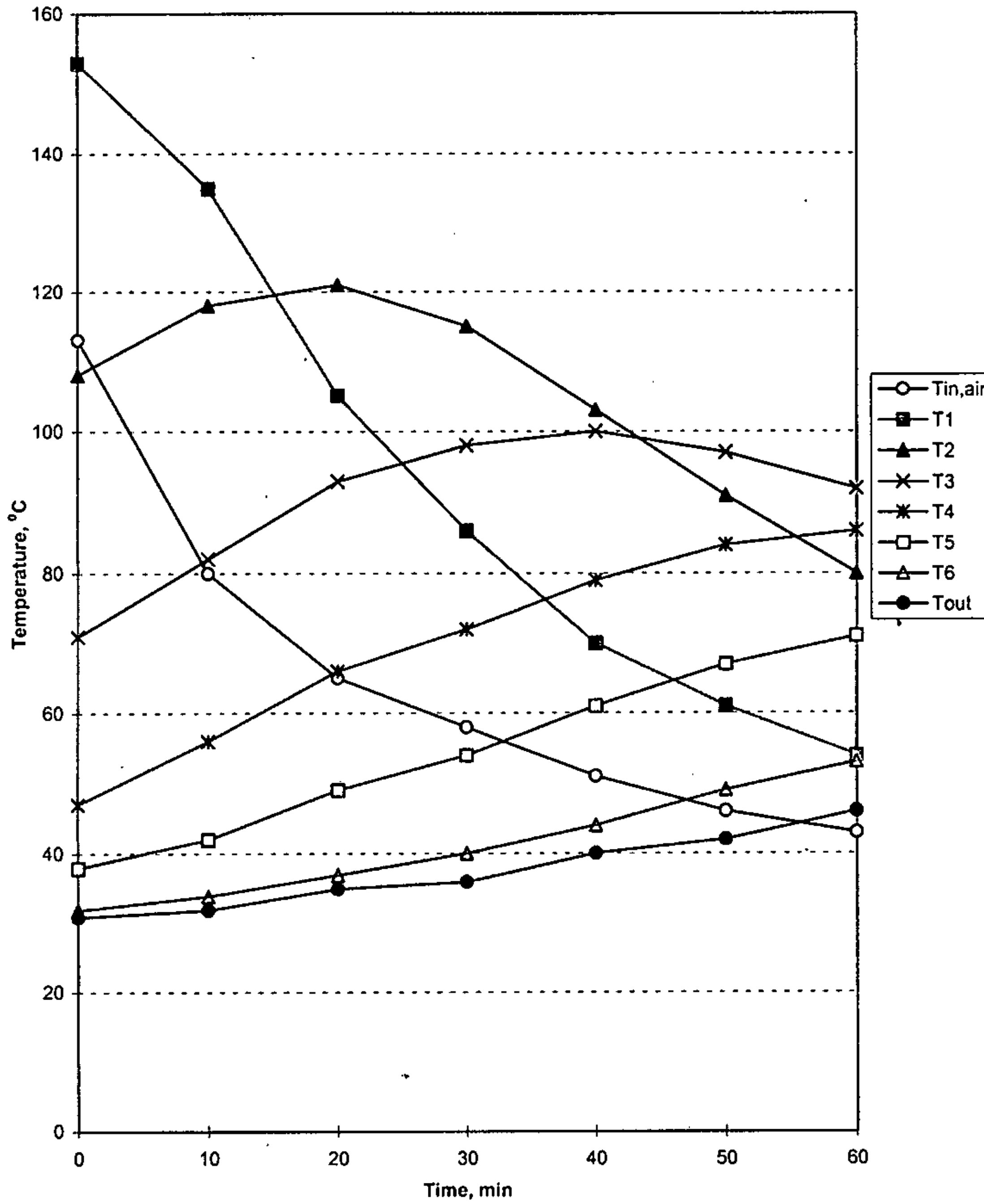


Fig. 6.1.3(b): Experimental Temperature vs. Time curves for first hour cooling (Case 3: Two cycles of 1 hr heating and 1 hr cooling)

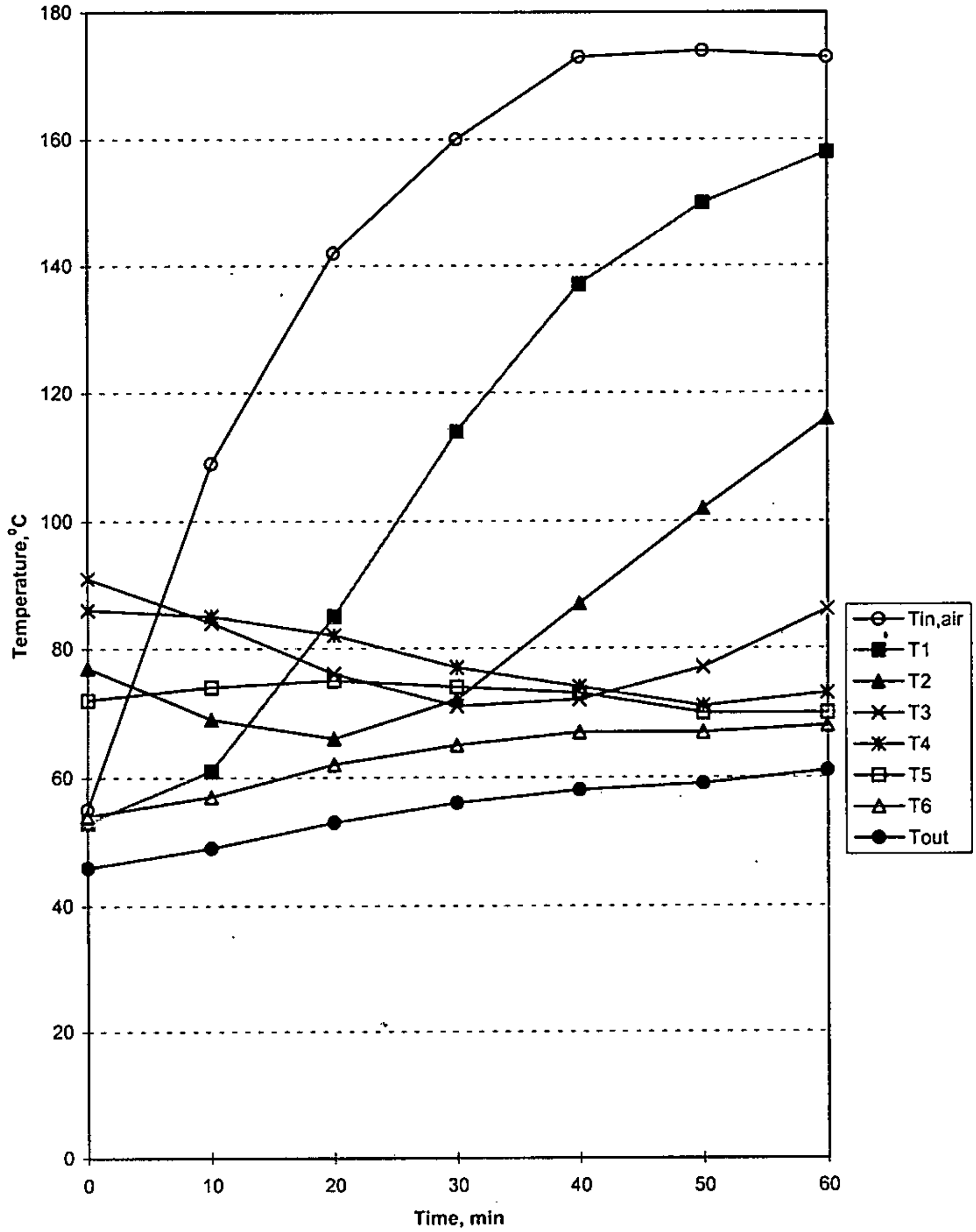


Fig. 6.1.3(c): Experimental Temperature vs. Time for second hour heating (Case 3: Two cycles of 1 hr heating and 1 hr cooling)

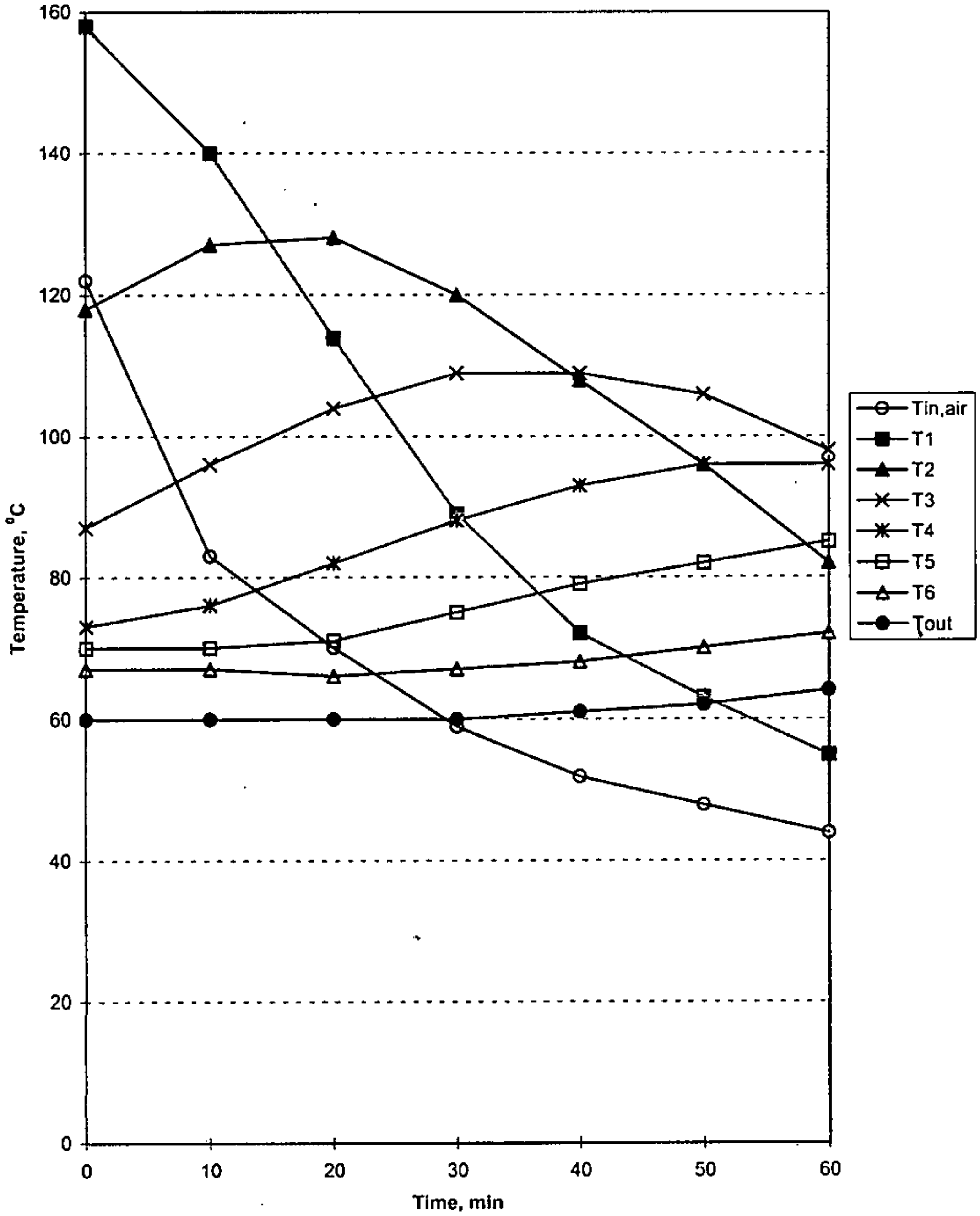


Fig. 6.1.3(d): Experimental Temperature vs.Time curves for second hour cooling (case 3: Two cycles of 1 hr heating and 1 hr cooling)

6.1.4 Case 4: 2 hours Heating and 2 hours Cooling

Since one hour heating and one hour cooling was not efficient for recovering heat both the heating and cooling cycles were increased to two hours. The experimental data are shown in Appendix-1 (Table 8.1.4(a) and 8.1.4(b)). During the heating cycle the average air flow rate was 362 litres/min and the average inlet hot air temperature was 159 ^{0}C. As shown in Fig. 6.1.4(a), the heating curves are identical to that of Case 2. The cooling characteristics of the bed are shown in Fig. 6.1.4(b). During cooling, the air flow rate was 360 litres/min and the average air temperature was 59 ^{0}C. One noteworthy feature from Fig. 6.1.4(b) is that all sections of the bed except the first don't start cooling until their temperatures become higher than that of the preceding sections. This is because the air becomes heated in the preceding section to a temperature higher than the bed temperature of the following section. Under this condition, the following section gets heated instead of being cooled.

6.1.5 Case 5 : 2 hours Heating and 2 hours Cooling, bed length 40 in.

As can be seen from Fig. 6.1.4(b), the uppermost section of the bed was not cooled at all during the two hours of the cooling cycle. Therefore, there was no utility of the topmost section of the bed. The bed length was decreased to 40 inches from 48 inches, i.e., the pebbles from the last section of the bed were removed. Two hours heating and two hours cooling of the bed were performed. The temperature curves are shown in Figs. 6.1.5(a) and 6.1.5(b) for heating and cooling, respectively. From Fig. 6.1.5(b), we see that the cooling characteristics have improved for the last section of the bed. It has cooled down to a larger extent.

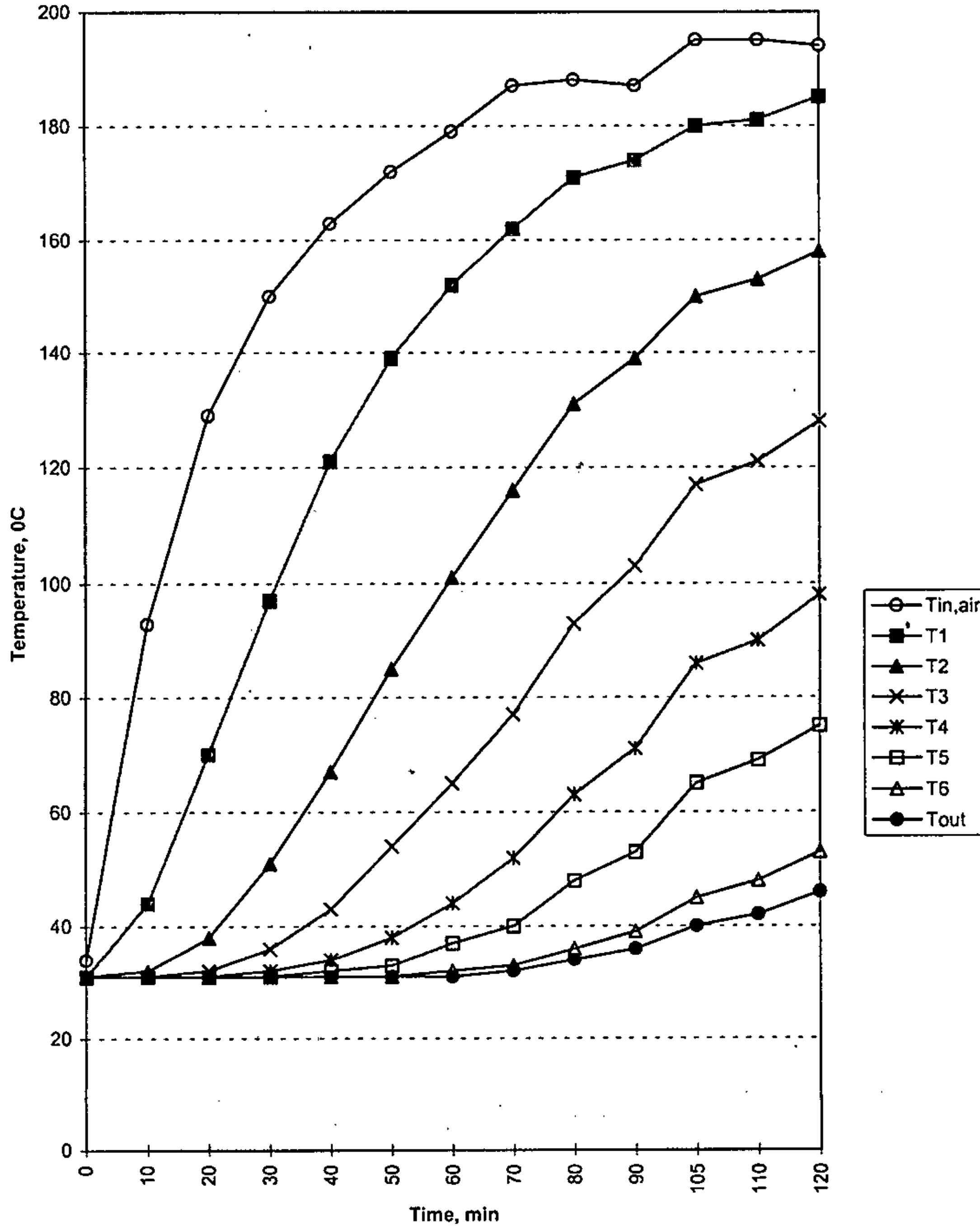


Fig. 6.1.4(a): Experimental Temperature vs. Time curves for heating (case 4: Two hours heating and two hours cooling)

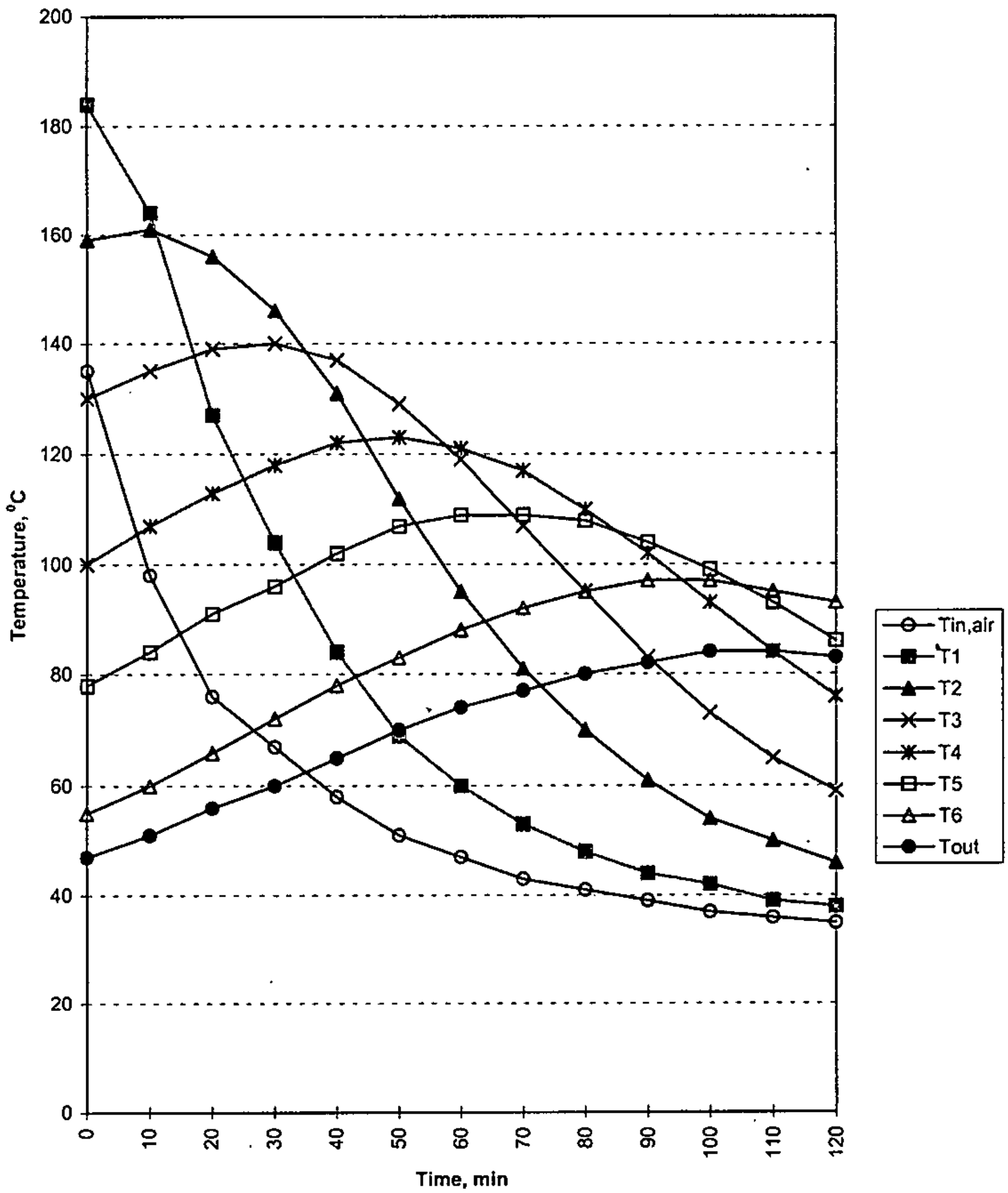


Fig. 6.1.4(b): Experimental Temperature vs. Time curves for cooling (Case 4: Two hours heating and two hours cooling)

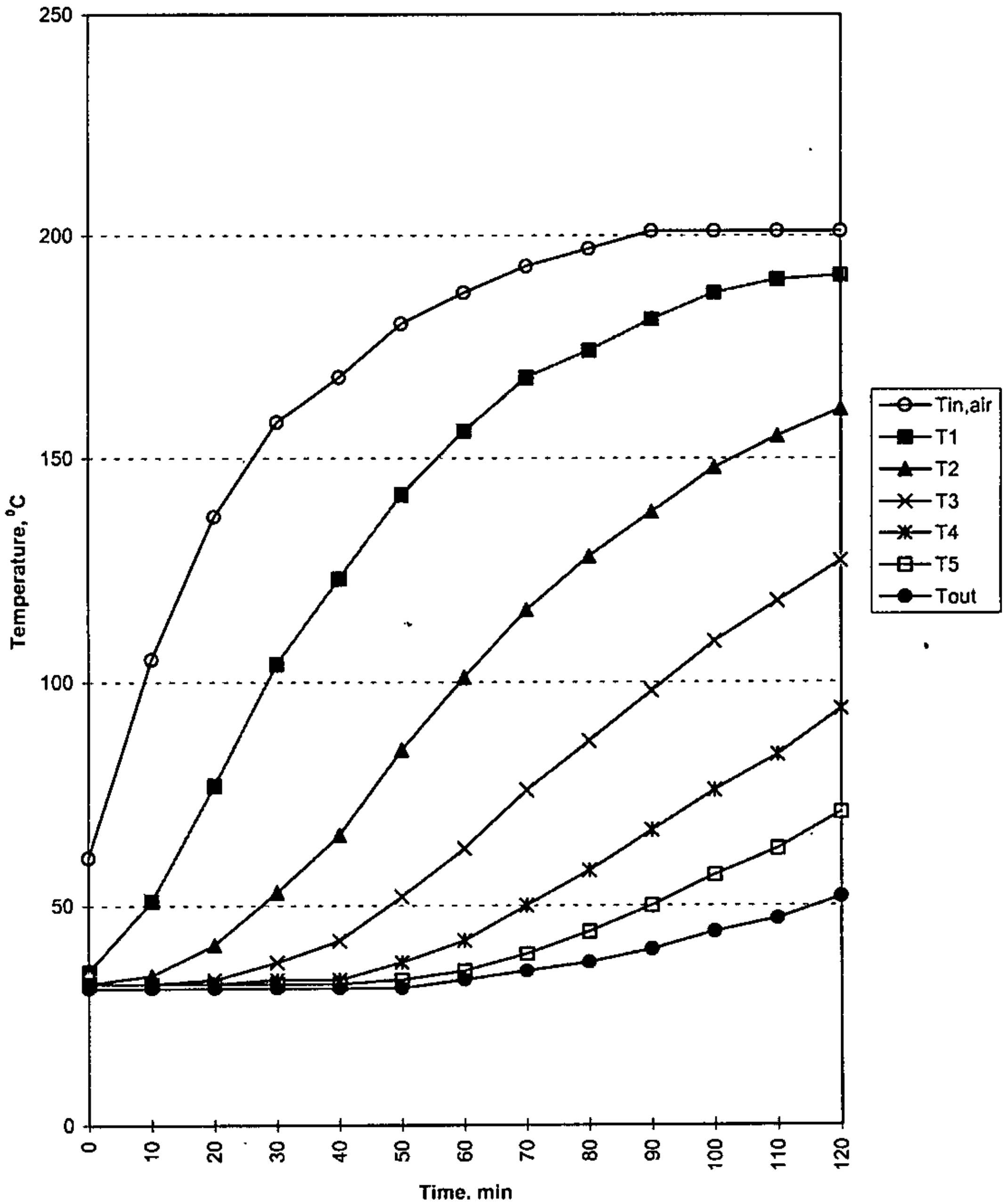


Fig. 6.1.5(a): Experimental Temperature vs Time curves for heating (case 5: Two hours heating and two hours cooling, bed length 40 inches)

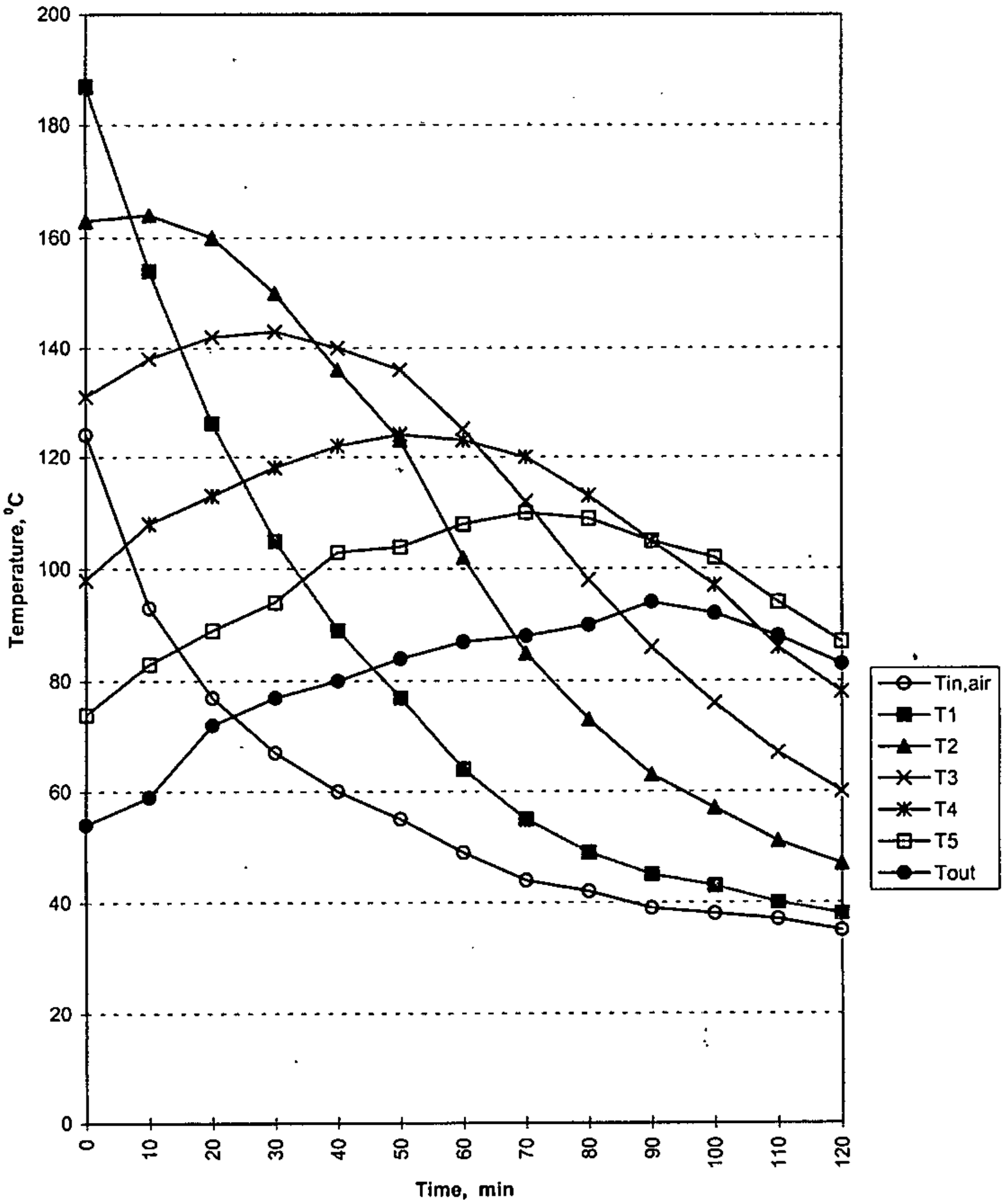


Fig. 6.1.5(b) : Experimental Temperature vs. Time curves for cooling (case 5: Two hours heating and two hours cooling, bed length 40 inches)

6.2 Modelling Results

A mathematical model was developed for simulation of the pebble bed heat regenerator. The model has been presented in Chapter 5. A FORTRAN program has been written to solve the model and simulate cases 4 and 5 discussed in the previous sections. For the model run, the following data were used:

Diameter of the pebbles, $D_p = 1$ inch,

Height of differential element, $\Delta z = 4$ inch,

Differential time interval, $\Delta t = 10$ min,

Porosity of the bed, $\varepsilon = 0.415$

Density of the pebbles, $\rho_s = 2650$ Kg/m^3

Density and specific heat of air are taken at its average temperature for a particular experiment.

A) Case 4: The results of the model runs, i.e., the temperatures of the various sections of the bed are plotted against time and given in Figs. 6.2.1(a) and 6.2.1(b). As can be seen, the shapes of all the curves are identical to that of the experimental curves of Figs. 6.1.4(a) and 6.1.4(b).

B) Case 5: Figs. 6.2.2(a) and 6.2.2(b) show the modelled results. A comparison between Fig. 6.2.2(a) and Fig. 6.1.5(a), and Fig. 6.2.2(b) and Fig. 6.1.5(b) reviewed that the experimental and modelled curves are identical in shape.

The good agreement between the experimental and the modelled results especially the manner in which it predicts the cooling cycle validates the model. A comparison between the modelled and experimental results for cases 4 and 5 is shown and discussed in the following section.

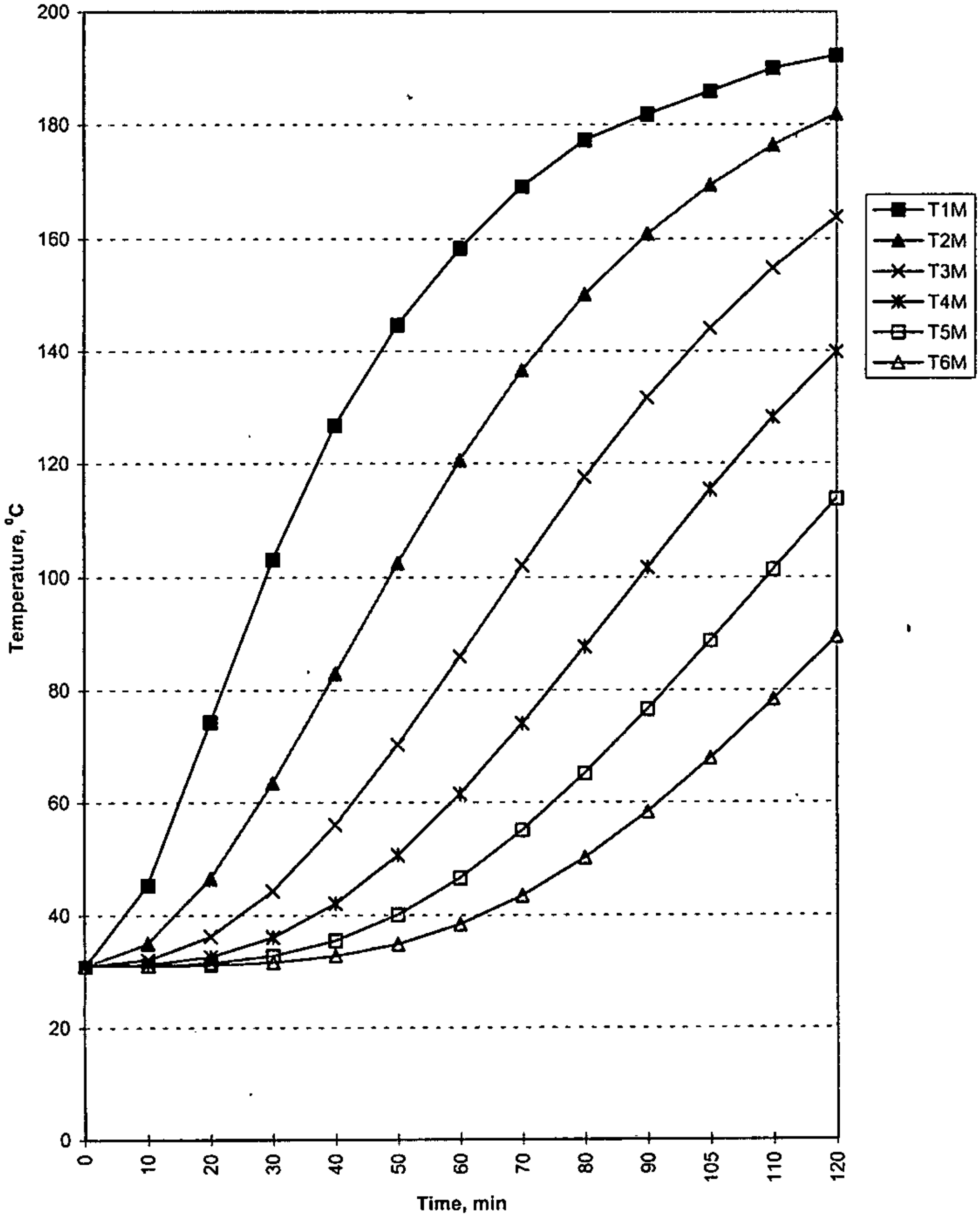


Fig. 6.2.1(a) : Modelled Temperature vs. Time curves for heating (case 4: Two hours heating and two hours cooling)

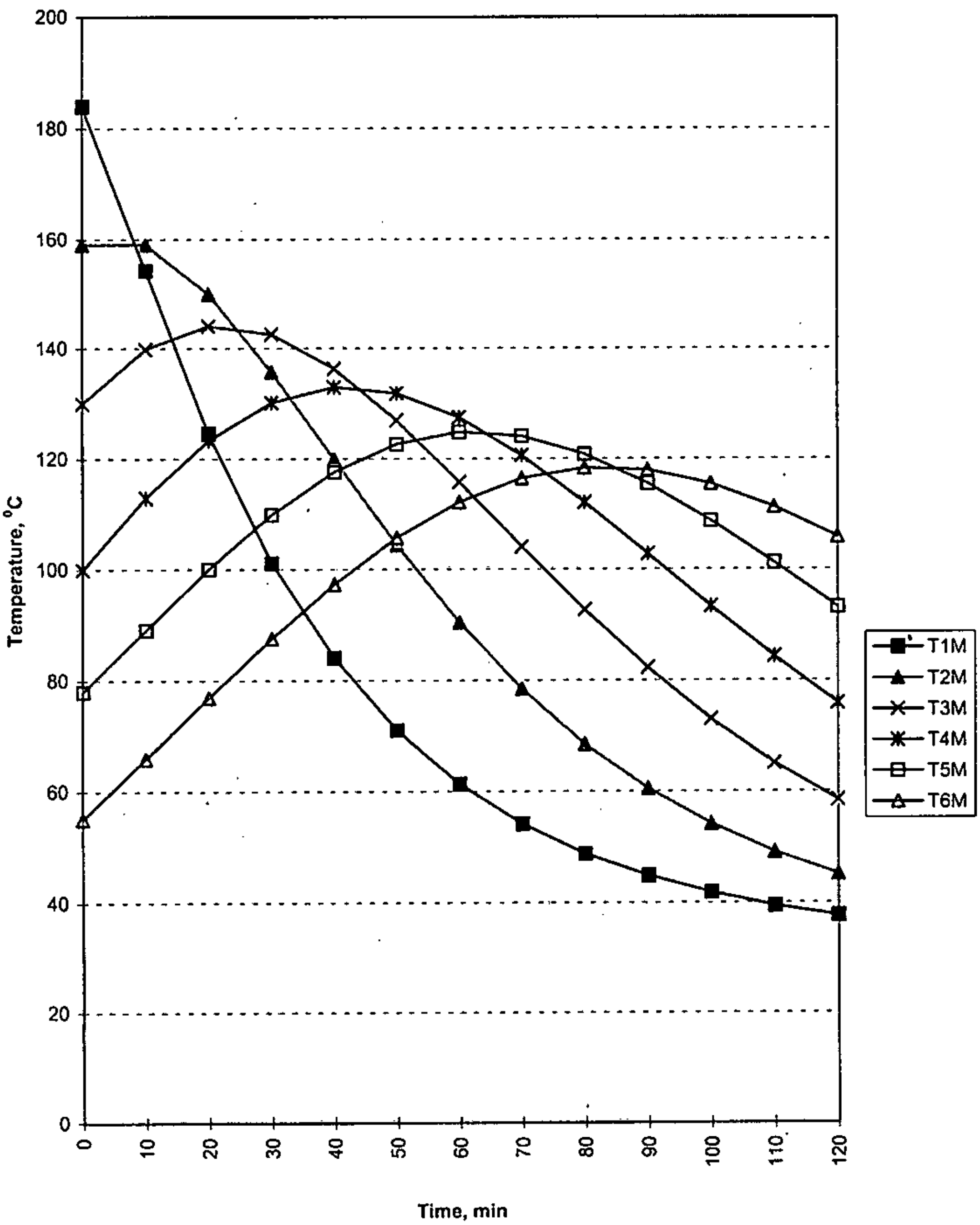


Fig. 6.2.1(b) : Modelled Temperature vs. Time Curves for cooling (Case 4: Two hours heating and two hours cooling)

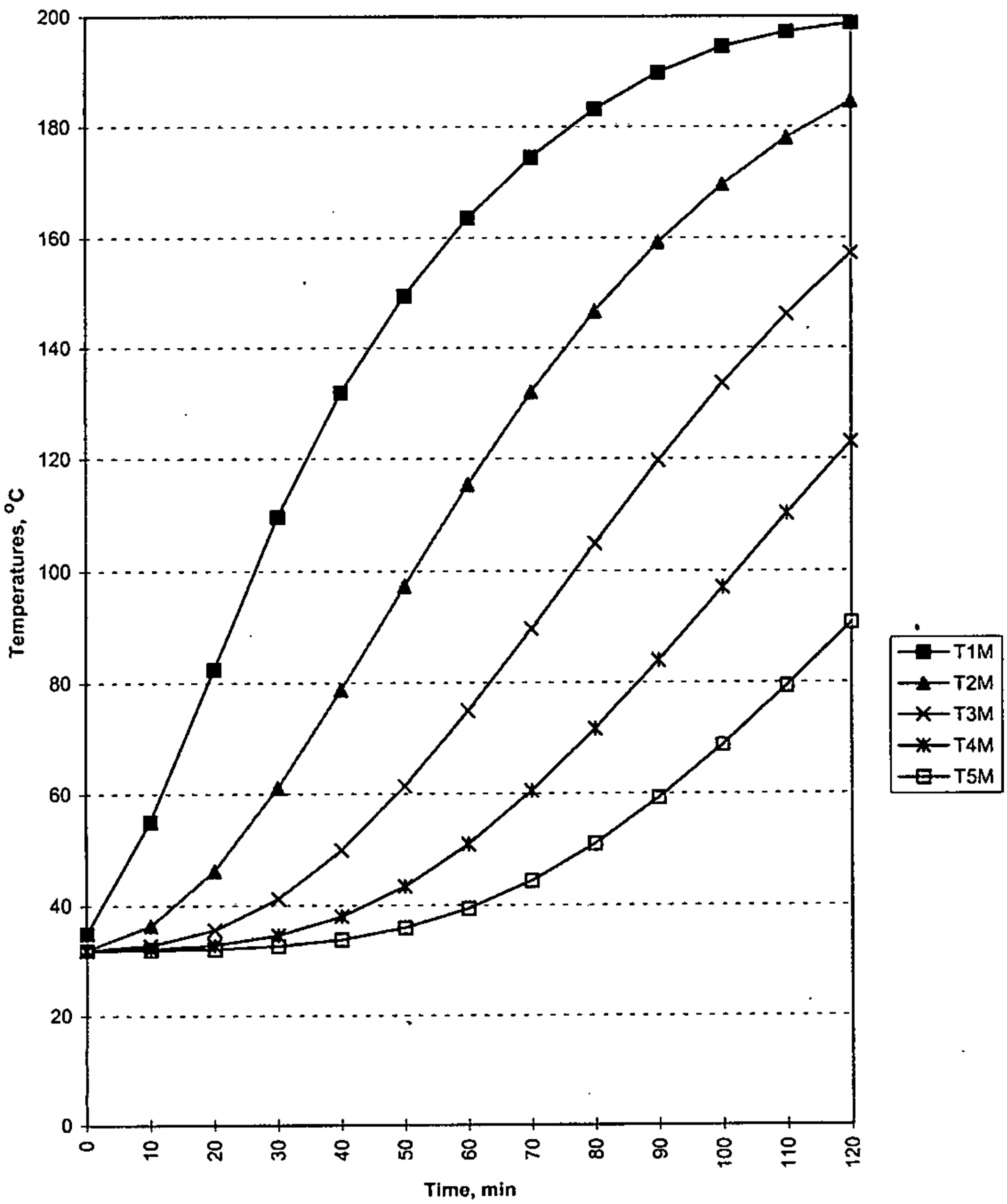


Fig. 6.2.2(a) : The modelled Results for heating (Case 5: Two hours heating and two hours cooling, bed length 40 inches)

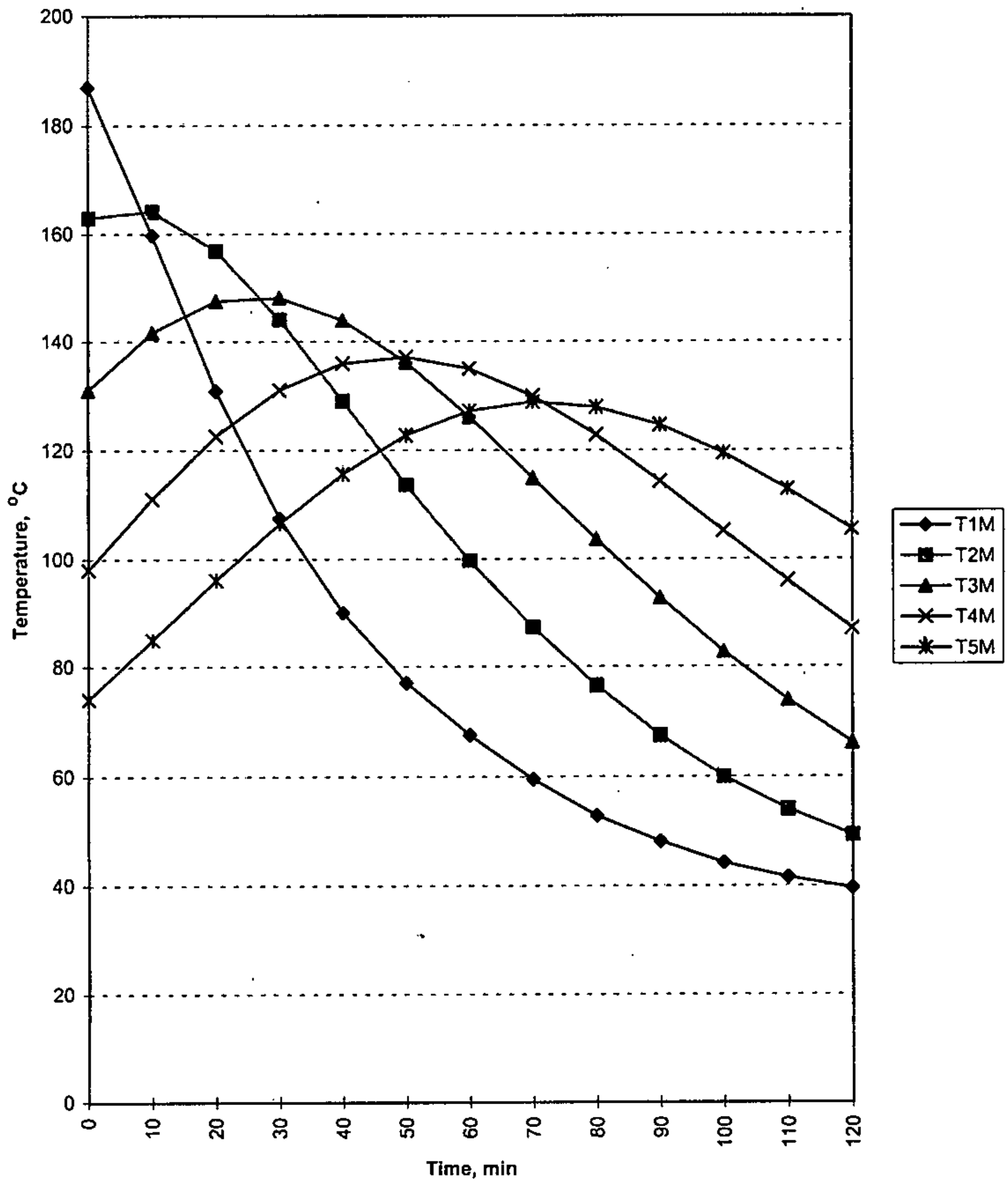


Fig. 6.2.2(b) : The modelled Results for cooling (Case 5: Two hours heating and two hours cooling, bed length 40 inches)

6.3 Comparison between the Modelled and Experimental Results

A) Case 4 :

Fig. 6.3.1(a) shows the comparison between the modelled temperatures and the experimental temperatures for the different sections of the bed for the heating cycle. From this figure, it can be seen that the deviations between the modelled and experimental results are very small for the first one hour of heating for all the points in the bed. This is because during this time the heat loss from the column was very small due to the low temperature of the bed. Since the model assumes a negligible heat loss from the bed, the deviation is small during the initial heating period but increases as time progresses. The heat loss from the column increased with the passage of time due to the increase of column temperature. Another point that is noteworthy from the figure is the increasing deviations with increasing distance from the column bottom, i.e., the deviation for the first point is smaller than that of the second point, and so on. It is worth pointing out that the entering air temperatures used in the model to calculate the temperatures of the first point of the bed were experimentally measured values and hence, the deviation for the first point is small. For the other sections the entering air temperatures were calculated from the model which assumes negligible heat loss from the column wall and therefore, these values are higher than the experimental values as can be seen from Fig. 6.3.1(a). This error of not accounting for heat loss from each section of the bed through column wall propagates from one section to the others. Thus the deviation is highest for the topmost section (section 6).

Figure 6.3.1(b) shows the comparison between the modelled and experimental results for case 4 cooling cycle. From the figure it can be seen that the deviation is large during the initial periods of cooling because at that time the temperature of the bed as well as column was high which leads to a large heat loss from the column. During the final periods of the cooling cycle, the deviations are very small because the low temperature of the bed leads to low heat loss. As can be seen from Fig. 6.3.1(b), during the final periods of cooling the deviation is very small for the first three sections of the bed but is high for the other sections. The reason for the small deviations for the first three sections is that the bed had cooled down considerably by the end of the cooling cycle. However, the other sections remained relatively hot thus causing higher heat loss and larger deviations.

B) Case 5 :

A comparison between the modelled and experimental results both for the heating and cooling cycles of case 5 is presented in Figs. 6.3.2(a) and 6.3.2(b). From Fig. 6.3.2(a), for the heating cycle, the deviations between the experimental and modelled results are minimum for the first section and maximum for the last section of the bed. This behaviour is identical to that of case 4. For the cooling cycle, the deviation is minimum at the end of the cycle and maximum during the initial periods of cooling. This is also similar to that of case 4. The underlying reasons for this type of behaviour have been discussed in the previous case.

The above discussions indicates that the model developed for simulation of the pebble bed regenerator is robust enough to calculate pebble bed parameters for good and efficient design.

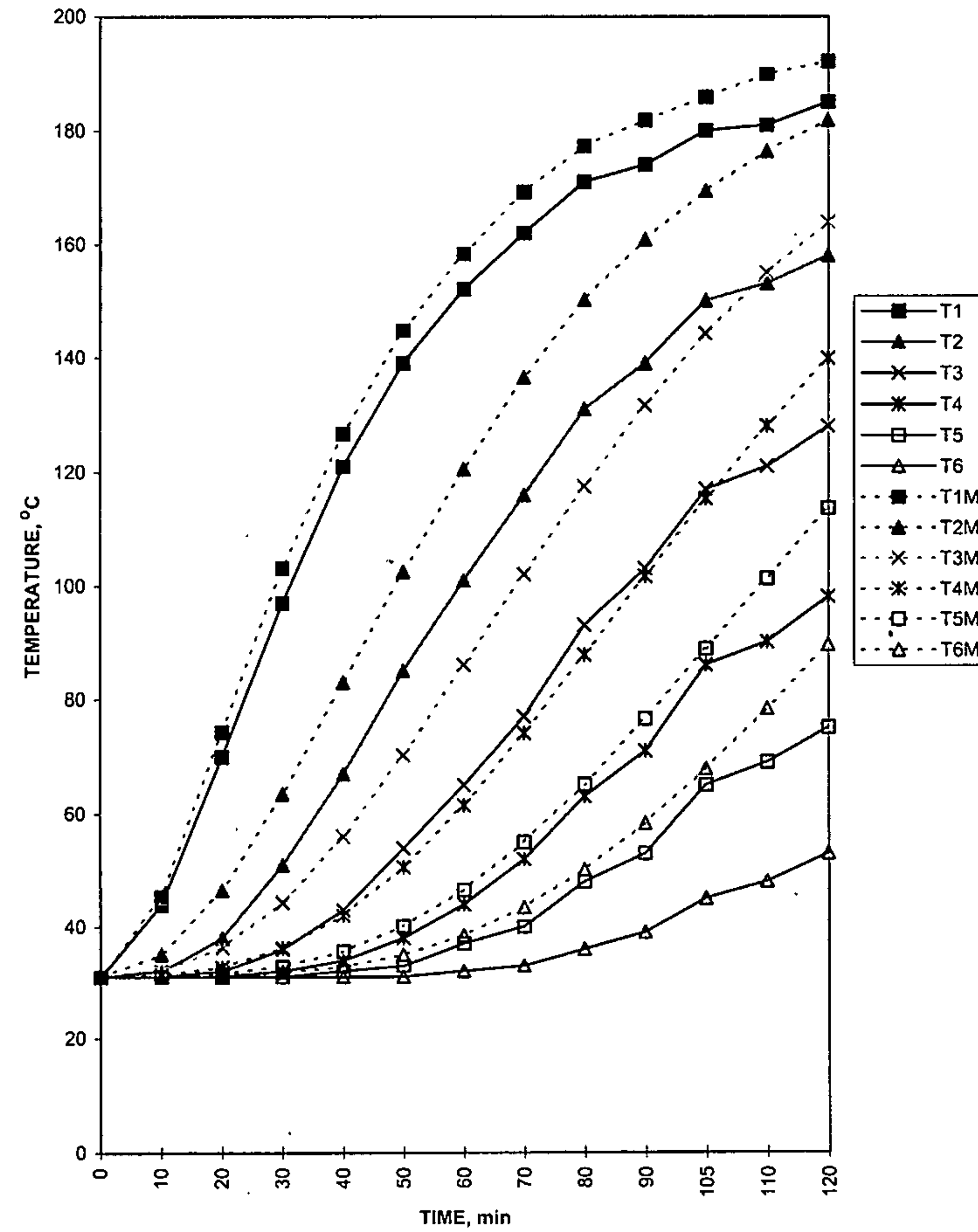


Fig. 6.3.1(a): Comparison between the Modelled and Experimental Temperatures for heating (Case 4: Two hours heating and two hours cooling)

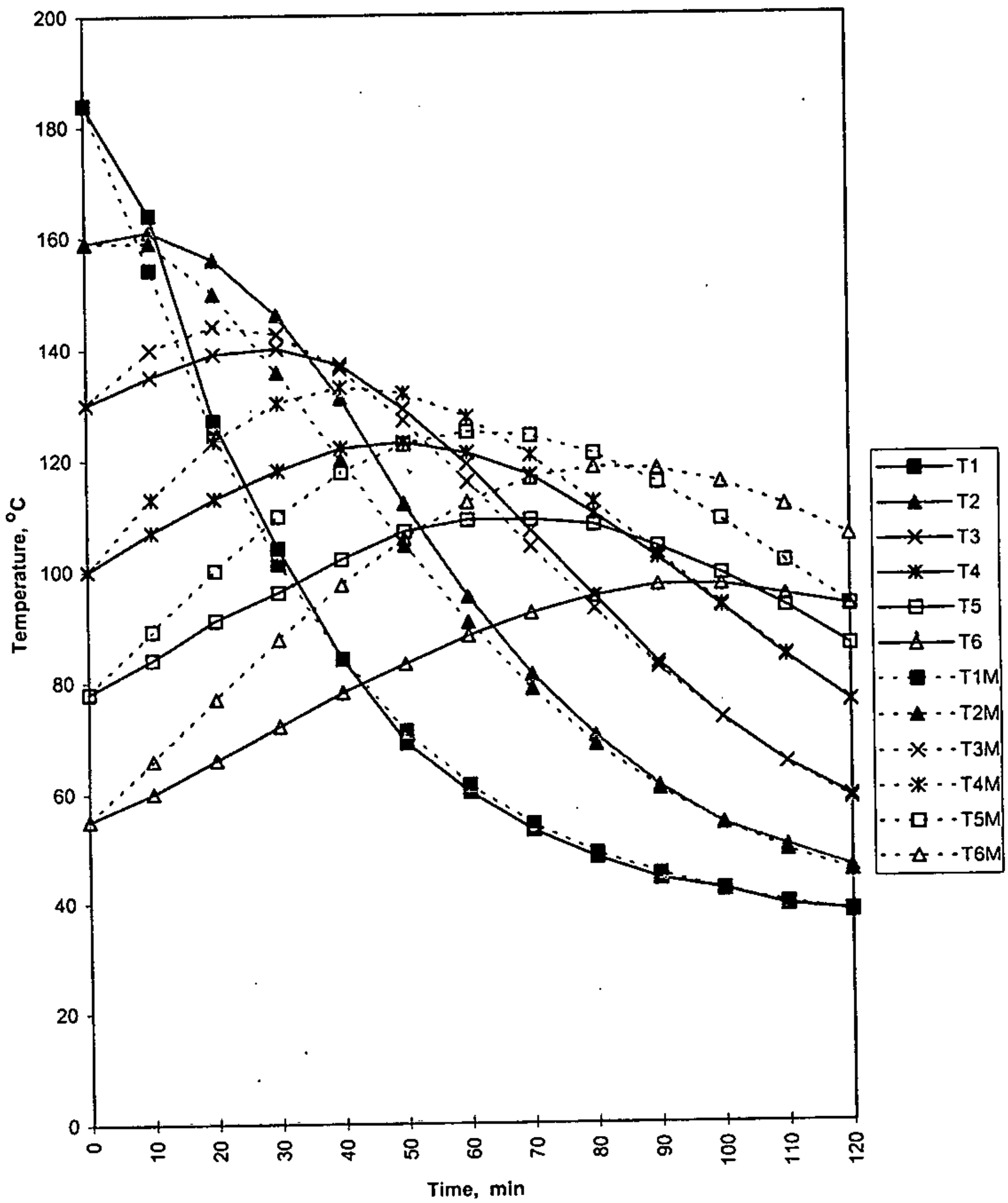


Fig. 6.3.1(b): Comparison between the Modelled and Experimental Temperatures for cooling (Case 4: Two hours heating and two hours cooling)

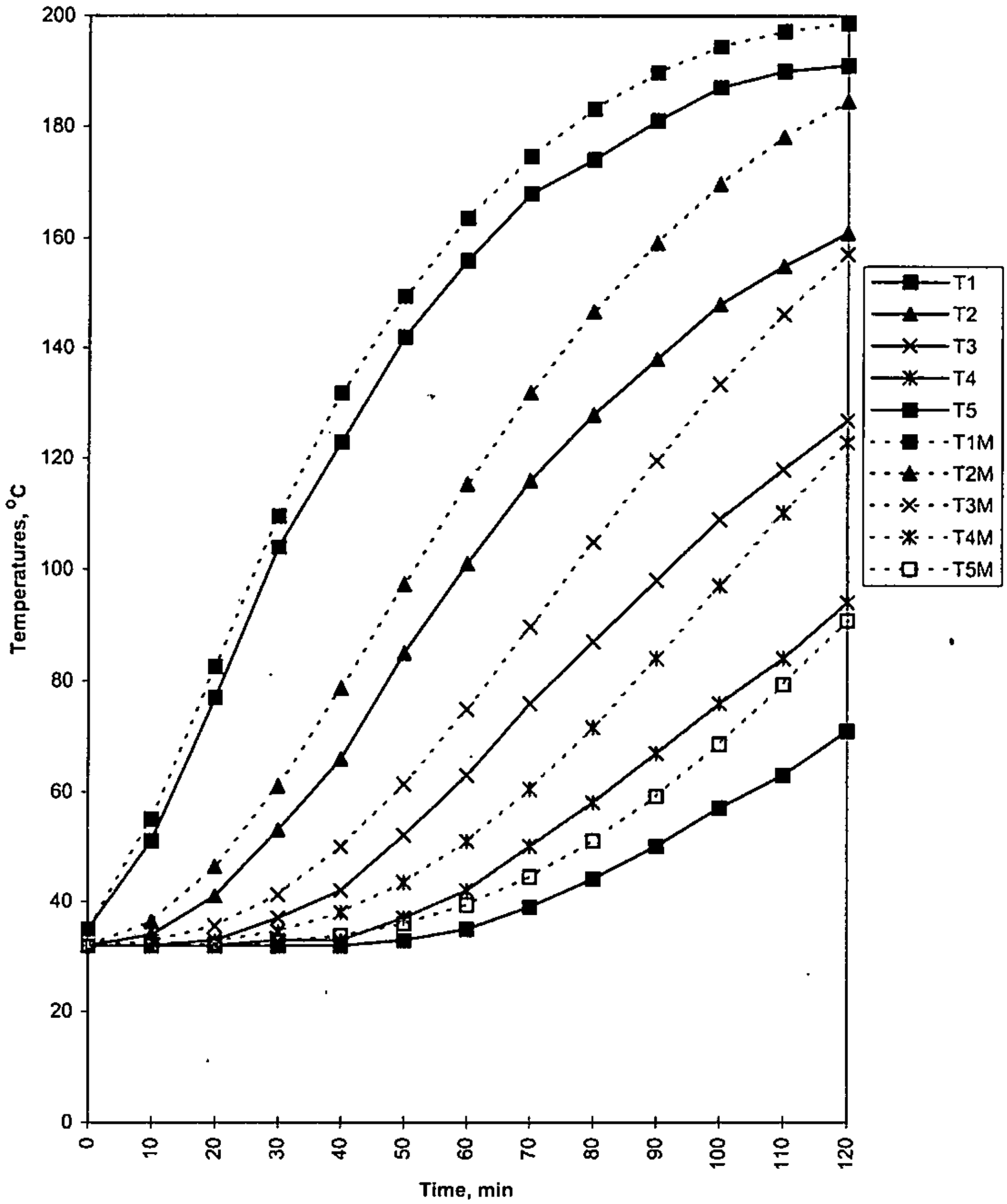


Fig. 6.3.2(a): Comparison between Experimental and Modelled Results for the heating Cycle (Case 5: Two hours heating and two hours cooling, bed length 40 inches)

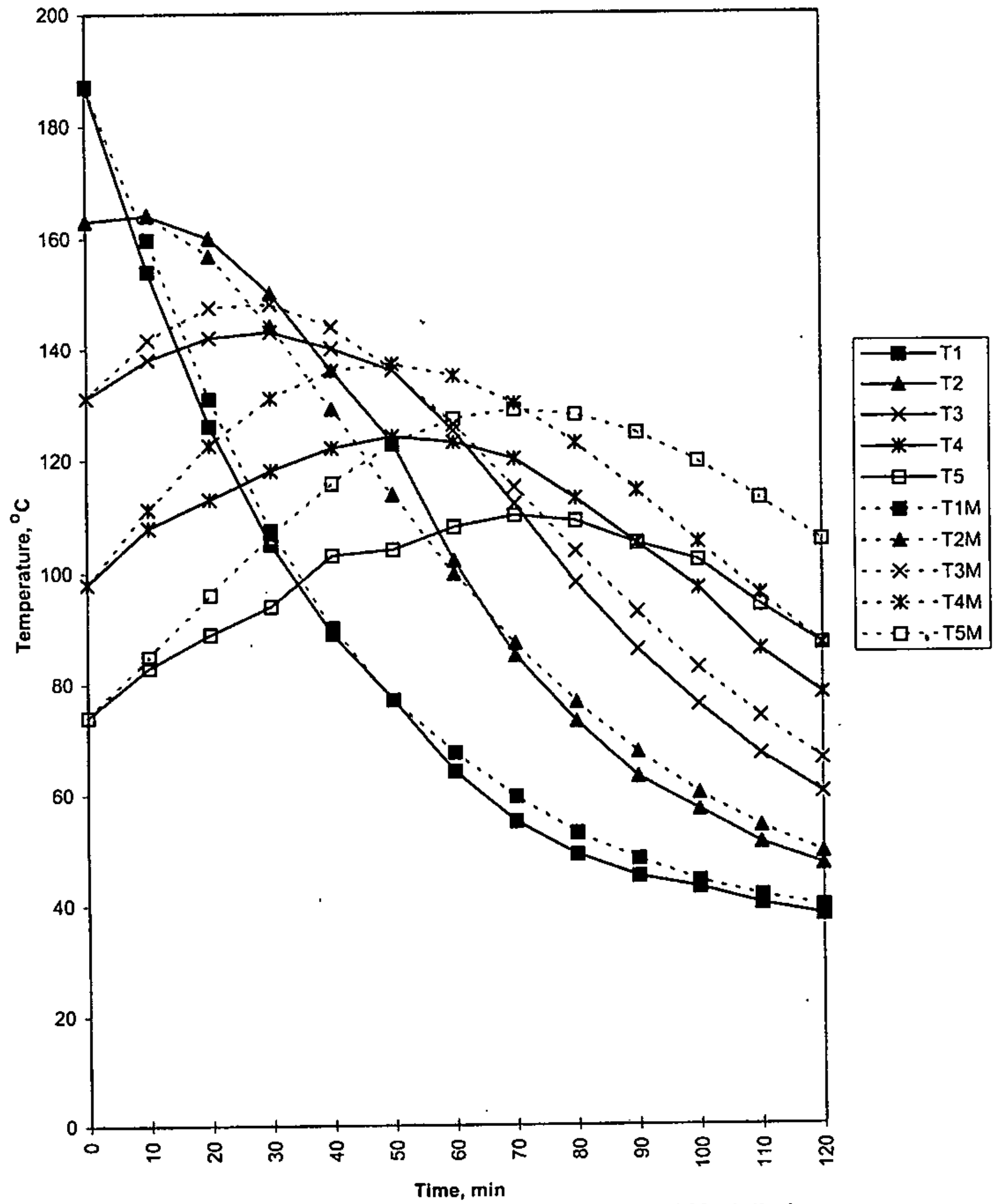


Fig. 6.3.2(b): Comparison between Experimental and Modelled Results for the heating Cycle (Case 5: Two hours heating and two hours cooling, bed length 40 inches)

6.4 Optimum Heating Time

At any given time, first the heat absorbed by each section of the bed was calculated. Then the total heat absorbed by the bed at that time is obtained by summing up the heat absorbed by all sections of the bed. The calculated data is given in Appendix-1 (Table 8.6.1(a)). By performing this calculation for all (10 minutes time) intervals for 340 minutes, the Fig. 6.4.1 is obtained. From the figure, it can be seen that the slope of the curve is steep in the first three hours but gradually flattens out. This implies that after three hours the bed heat absorbing capacity had considerably diminished. So the optimum time for heating can be taken as three hours. However, in this experimental set-up the column suffered large heat loss. The optimum heating time would probably have been lower had heat loss been minimised.

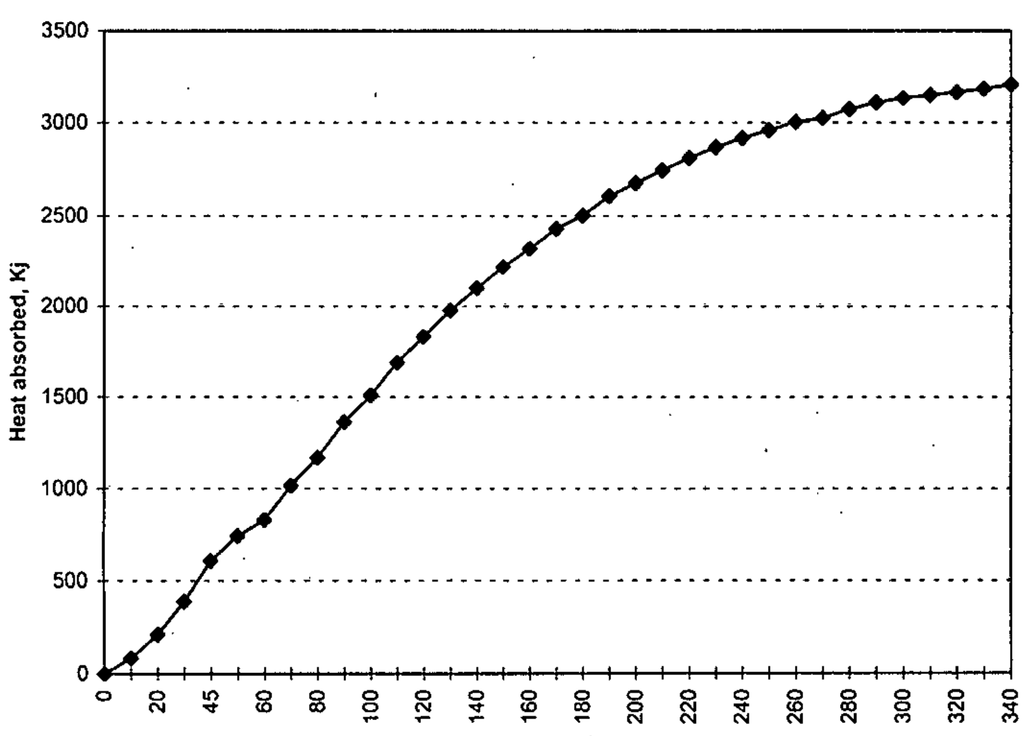


Fig. 6.4.1 : Heat absorbed by the bed vs. Time

CHAPTER VII

CONCLUSIONS

7.1 CONCLUSION

The objectives of this project work were to develop a mathematical model for pebble bed heat regenerators, to generate new accurate experimental data, and compare the experimental data with the modelled results for checking the robustness of the model. Experiments were performed for five different cases. The bed temperatures determined from the experiment can be assumed to be accurate because the thermocouples were fixed into the centre of the stones by drilling the stones. This is one of the significant features of the experiment. The model developed has been shown to be very flexible because the single model has been used both for the heating and cooling cycles. The experimental and modelled results are compared for two cases. Such comparison for all the cases and predictions for other cases can easily be performed. The deviation between the experimental and modelled results are minimum at the bottom of the column and maximum at the upper part of he column. However, for most of the cases the deviations were in the range of 10 to 20%. The main shortcoming of the model is the assumption of negligible heat loss from the column wall. The deviations between the experimental and modelled results are due to this assumption. The optimum heating time for case one was also determined and found to be three hours.

7.2 SUGGESTIONS FOR FUTURE WORKS

Various constraints of the experiment and lack of facilities prevented the investigation from being complete. Some of the things that can be done to improve the present work are given below:

1. During the experiment the temperature readings of the thermocouples are taken one by one but they should be taken simultaneously. It introduced some errors in the readings. It is recommended that a data acquisition system should be used in future.
2. The effect of bed length and bed diameter on the parameters of the packed bed heat regenerator should be studied in future work.
3. Counter-current operations of the column during the cooling cycle can be studied to compare the efficiencies of the column for the two types of operation.
4. The model should be enhanced to account for the unsteady state heat loss from the column wall.
5. The optimum flow rate of air for obtaining maximum recovery of heat in the cooling cycle should be studied.
6. The column and connecting pipes should be insulated very well so that the heat loss from the column is minimised.
7. Specific heat and thermal conductivity of the pebbles should be determined in the laboratory.

NOMENCLATURE

a	-	area of stones heat transfer surface /ft^3 of column, ft^2/ft^3.
A	-	dimensionless constant
B	-	dimensionless constant
C	-	dimensionless constant
C_a	-	specific heat of air, kj/kg, °C
C_s	-	specific heat of stone, kj/kg, °C
D	-	dimensionless constant
D	-	diffusion co-efficient
D_p	-	diameter of the pebbles, in
h	-	convective heat transfer coefficient of air, Btu/hr.ft^2.°F
M_a	-	mass flow rate of air, kg/min
M	-	dimensionless constant
N	-	dimensionless constant
PCM	-	phase Changing Materials
S	-	cross-sectional area of the column, ft^2
t	-	time, min
T	-	temperature of air, °C
TA	-	temperature of air, °C
TP	-	temperature of pebbles, °C
W	-	weight of stone, kg
z	-	direction for the height of the column

Greek symbols

ε	-	porosity
θ	-	temperature of stones, °C
ρ_s	-	density of stone, kg/m^3
σ^2	-	variance which characterizes S-shaped temperature vs. distance curve for solids
Δt	-	time interval

Δz	-	height of differential element.

Subscripts

m	-	distance increment
n	-	time increment.
a	-	air
s	-	stones or pebbles

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APPENDIX - 1

TABLE 8.1.1(a): EXPERIMENTAL DATA FOR HEATING (CASE 1)

			TEMPERATURES OF THE BED, °C						
Time,min	air flow rate,l/min	$T_{in, air}$, °C	T1	T2	T3	T4	T5	T6	$T_{out,air}$, °C
0	380	40	31	31	31	31	31	31	31
10	340	66	41	32	31.2	31.1	31	31	31
20	360	74	53.3	35.6	32	31.1	30.8	30.7	30.6
33	370	83.3	65.7	43.5	34.5	31.5	30.9	30.6	30.5
45	340	91.6	75.8	53.5	40.1	33.8	31.2	31	30.9
55	360	97.1	81	59.5	44.2	35.7	31.7	31.2	31
60	360	99.1	84.4	62.9	47.1	37.2	32	31.2	30.9
70	340	103	89.9	69.1	52.5	40.7	35.3	31.9	31.3
80	340	104.3	94.2	74.3	57	44.1	37.5	32.4	31.4
90	320	109.1	98.8	79.5	62.8	48.9	40.9	34.3	32.5
100	380	113.2	101.8	83.4	67	52.6	43.8	35.6	33.3
110	380	115.2	104.7	87.8	71.8	57.2	47.7	38.5	35.1
120	380	116.9	107.1	91.4	75.6	60.9	50.8	40.5	36.1
130	340	117	109.2	94.2	79.6	64.9	54.7	43.2	38.2
140	320	118	111	96.7	82.2	68.5	57.3	45.9	39.1
150	360	120	112.2	99	84.9	71.5	60.8	49.1	41.8
160	360	121.1	113.3	101	87.5	74.3	63.4	51.5	43.5
170	360	121.5	115	102.9	90	77.1	66	54.3	46.7
180	320	121.2	115.6	103.6	91.4	79.1	68.4	56.5	48.1
190	350	123	116.8	105.2	93.5	81.9	71.5	59.7	50.8
200	380	124	117.5	106.7	95	83.5	73.2	61.6	52.4
210	370	124.5	118.1	107.3	96.4	85.5	75.3	64	54.3
220	370	125	118.7	108.2	97.5	86.9	77.5	66.4	56.7
230	340	124.5	118.9	109.1	98.9	88.7	79.1	68.4	57.9
240	340	124.4	119.9	110.1	99.9	90	80.1	69.6	59.1
250	330	124.8	120.1	110.6	100.5	90.9	81.6	71.3	60.7
260	360	126.2	120.4	111.2	101.5	91.9	82.8	73	61.2
270	360	126.3	120.5	111.5	101.4	92.4	83.7	74.1	63.1
280	360	127.1	121.2	112	102.6	93.6	84.8	75.7	64.4
290	340	126.1	121.3	112.6	102.8	94.3	86.2	77.3	65.5
300	340	126.1	121.7	112.8	103.4	95	86.7	78	66.3
310	330	126.4	121.9	113	103.6	95.1	87.2	78.9	67
320	340	126.8	121.9	113.5	103.7	95.7	87.5	79.5	67.2
330	360	127.4	122	113.2	104	96	88.5	80.4	68.4
340	340	127	122.2	113.8	104.7	96.7	89	81	69.9

TABLE 8.1.1(b): EXPERIMENTAL DATA FOR COOLING (CASE 1)										
			TEMPERATURES OF THE BED, °C							
Time,min	air flow rate,l/min	$T_{in, air}$, °C	T1	T2	T3	T4	T5	T6	$T_{out,air}$, °C
0	380	117	122.1	113.7	104.4	96.3	89	81.2	69.6
10	360	92	117.1	113.6	104.8	97	89	81.7	70.6
20	340	72.9	103.8	112	105	97.6	90.3	82.7	71.4
30	340	61.2	87.3	106.7	104.1	97.6	90.7	83.4	71.5
45	330	50.9	67.8	93.4	99.8	97	90.5	83.6	71.5
50	340	48.4	63	88.5	97.2	96.3	90.6	83.9	72.1
60	370	44.4	55.7	82.4	91.7	94.4	89.7	83.9	72.1
70	370	41.6	50.2	70	84.7	91.1	88.6	83.7	72.3
80	380	39.3	45.7	61.8	77.1	86.7	86.6	83.8	72.7
90	360	38.1	43	56.1	70.4	81.6	83.7	82.9	72.4
100	350	36.8	40.6	51.1	64	76.5	80.5	81.6	72
110	370	35.5	38.5	46.5	57.4	69.8	75.5	79.5	71.2
120	350	34.9	37.2	43.7	52.8	64.5	71.1	76.9	69.3
130	340	34.3	36.1	41.3	48.9	59.5	66.8	74.3	67.9
140	360	33.8	35.3	39.6	45.9	55.3	62.4	70.9	65.9
150	380	33.3	34.5	37.9	42.9	50.8	57.5	66.9	63.5

TABLE 8.1.2(a): EXPERIMENTAL DATA FOR HEATING (CASE 2)

			TEMPERATURES OF THE BED, °C						
Time,min	air flow rate,l/min	$T_{in, air}$, °C	T1	T2	T3	T4	T5	T6	$T_{out,air}$, °C
0	400	36	31	31	31	31	31	31	31
10	400	101	43	32	31	31	31	31	31
20	400	134	75	39	32	31	31	31	31
30	400	153	106	55	37	32	31	31	31
40	400	164	128	73	46	34	32	31	31
53	400	170	146	96	61	41	35	31	31
60	340	174	154	109	71	47	38	32	31
70	410	181	161	122	85	56	43	33	32
80	420	185	168	134	98	67	50	37	34
93	400	187	173	142	110	80	60	42	37
100	350	186	175	148	117	87	65	46	40
110	340	187	177	153	125	96	74	52	44
122	360	188	181	158	133	106	84	60	49
131	390	190	182	162	139	112	90	66	54
140	400	191	183	164	142	118	97	72	59
150	380	191	183	167	146	123	103	78	64
160	370	190	184	169	149	129	109	85	69
170	350	190	185	169	151	132	113	90	72
180	400	191	185	170	153	135	117	96	77

TABLE 8.1.2(b): EXPERIMENTAL DATA FOR COOLING (CASE 2)									
			TEMPERATURES OF THE BED, °C						
Time, min	Air flow rate, l/min	$T_{in,air}$	T1	T2	T3	T4	T5	T6	$T_{out,air}$
0	400	175	185	170	153	135	117	96	77
10	360	127	172	169	155	138	122	101	82
20	400	97	147	166	156	140	125	106	86
30	430	77	121	157	154	142	127	109	89
40	430	65	98	141	149	142	129	112	97
50	430	56	80	123	140	140	130	115	99
60	420	50	67	105	129	136	129	117	102
70	415	46	58	89	116	130	127	118	104
80	380	43	52	76	103	121	123	118	105
90	350	40	47	65	89	110	116	117	104
100	400	39	44	58	78	100	110	114	102
110	405	37	41	51	67	89	101	110	100
120	410	36	39	47	60	78	92	105	97
130	440	35	38	44	54	70	83	99	94
140	440	35	37	41	49	63	75	92	89
150	440	34	35	39	45	56	67	84	83
160	420	34	35	38	43	52	61	77	77

TABLE 8.1.3(a): EXPERIMENTAL DATA FOR FIRST HOUR HEATING (CASE 3)

			TEMPERATURES OF THE BED, °C						
Time,min	air flow rate,l/min	Tin, air, °C	T1	T2	T3	T4	T5	T6	Tout,air, °C
0	360	40	31	31	31	31	31	31	31
10	360	111	58	35	31	31	31	31	31
20	360	131	82	43	33	32	31	31	31
30	380	154	106	57	38	33	31	31	31
40	360	167	128	74	47	35	32	31	31
50	360	172	142	90	57	40	34	31	31
60	360	172	153	105	68	46	37	32	31

TABLE 8.1.3(b): EXPERIMENTAL DATA FOR FIRST HOUR COOLING (CASE 3)

			TEMPERATURES OF THE BED, °C						
Time,min	air flow rate,l/min	Tin, air, °C	T1	T2	T3	T4	T5	T6	Tout,air, °C
0	360	113	153	108	71	47	38	32	31
10	360	80	135	118	82	56	42	34	32
20	360	65	105	121	93	66	49	37	35
30	360	58	86	115	98	72	54	40	36
40	360	51	70	103	100	79	61	44	40
50	370	46	61	91	97	84	67	49	42
60	360	43	54	80	92	86	71	53	46

TABLE 8.1.3(c): EXPERIMENTAL DATA FOR SECOND HOUR HEATING (CASE 3)

			TEMPERATURES OF THE BED, °C						
Time,min	air flow rate,l/min	Tin, air, °C	T1	T2	T3	T4	T5	T6	Tout,air, °C
0	360	55	53	77	91	86	72	54	46
10	360	109	61	69	84	85	74	57	49
20	360	142	85	66	76	82	75	62	53
30	360	160	114	72	71	77	74	65	56
40	370	173	137	87	72	74	73	67	58
50	370	174	150	102	77	71	70	67	59
60	360	173	158	116	86	73	70	68	61

TABLE 8.1.3(d): EXPERIMENTAL DATA FOR SECOND HOUR COOLING (CASE 3)

			TEMPERATURES OF THE BED, °C						
Time,min	air flow rate,l/min	Tin, air, °C	T1	T2	T3	T4	T5	T6	Tout,air, °C
0	360	122	158	118	87	73	70	67	60
10	360	83	140	127	96	76	70	67	60
20	360	70	114	128	104	82	71	66	60
30	360	59	89	120	109	88	75	67	60
40	360	52	72	108	109	93	79	68	61
50	360	48	63	96	106	96	82	70	62
60	360	44	55	82	98	96	85	72	64

TABLE 8.1.4(a): EXPERIMENTAL DATA FOR HEATING (CASE 4)

			TEMPERATURES OF THE BED, °C						
Time,min	air flow rate,l/min	$T_{in, air}$, °C	T1	T2	T3	T4	T5	T6	$T_{out,air}$, °C
0	400	34	31	31	31	31	31	31	31
10	380	93	44	32	31	31	31	31	31
20	360	129	70	38	32	31	31	31	31
30	380	150	97	51	36	32	31	31	31
40	380	163	121	67	43	34	32	31	31
50	380	172	139	85	54	38	33	31	31
60	360	179	152	101	65	44	37	32	31
70	360	187	162	116	77	52	40	33	32
80	340	188	171	131	93	63	48	36	34
90	340	187	174	139	103	71	53	39	36
105	350	195	180	150	117	86	65	45	40
110	340	195	181	153	121	90	69	48	42
120	330	194	185	158	128	98	75	53	46

TABLE 8.1.4(b): EXPERIMENTAL DATA FOR COOLING (CASE 4)

			TEMPERATURES OF THE BED, °C						
Time,min	air flow rate,l/min	$T_{in, air}$, °C	T1	T2	T3	T4	T5	T6	$T_{out,air}$, °C
0	360	135	184	159	130	100	78	55	47
10	360	98	164	161	135	107	84	60	51
20	360	76	127	156	139	113	91	66	56
30	360	67	104	146	140	118	96	72	60
40	360	58	84	131	137	122	102	78	65
50	360	51	69	112	129	123	107	83	70
60	360	47	60	95	119	121	109	88	74
70	360	43	53	81	107	117	109	92	77
80	360	41	48	70	95	110	108	95	80
90	360	39	44	61	83	102	104	97	82
100	360	37	42	54	73	93	99	97	84
110	360	36	39	50	65	84	93	95	84
120	360	35	38	46	59	76	86	93	83

TABLE 8.1.5(a): EXPERIMENTAL DATA FOR HEATING (CASE 5)								
			TEMPERATURES OF THE BED, °C					
Time,min	air flow rate,l/min	$T_{in, air,}$ °C	T1	T2	T3	T4	T5	$T_{out,air,}$ °C
0	360	61	35	32	32	32	32	31
10	320	105	51	34	32	32	32	31
20	300	137	77	41	33	32	32	31
30	350	158	104	53	37	33	32	31
40	350	168	123	66	42	33	32	31
50	320	180	142	85	52	37	33	31
60	300	187	156	101	63	42	35	33
70	290	193	168	116	76	50	39	35
80	290	197	174	128	87	58	44	37
90	310	201	181	138	98	67	50	40
100	290	201	187	148	109	76	57	44
110	310	201	190	155	118	84	63	47
120	290	201	191	161	127	94	71	52

TABLE 8.1.5(b): EXPERIMENTAL DATA FOR COOLING (CASE 5)								
			TEMPERATURES OF THE BED, °C					
Time,min	air flow rate,l/min	$T_{in, air,}$ °C	T1	T2	T3	T4	T5	$T_{out,air,}$ °C
0	340	124	187	163	131	98	74	54
10	320	93	154	164	138	108	83	59
20	320	77	126	160	142	113	89	72
30	420	67	105	150	143	118	94	77
40	360	60	89	136	140	122	103	80
50	330	55	77	123	136	124	104	84
60	380	49	64	102	125	123	108	87
70	400	44	55	85	112	120	110	88
80	310	42	49	73	98	113	109	90
90	370	39	45	63	86	105	105	94
100	350	38	43	57	76	97	102	92
110	390	37	40	51	67	86	94	88
120	410	35	38	47	60	78	87	83

TABLE 8.2.1 (a) : MODELLED RESULTS FOR HEATING (CASE 4)

	Temperature of the bed, °C					
Time,min	T1M	T2M	T3M	T4M	T5M	T6M
0	31	31	31	31	31	31
10	45.35	35.09	32.17	31.33	31.09	31.03
20	74.34	46.52	36.33	32.78	31.58	31.19
30	103.12	63.46	44.34	36.17	32.92	31.69
40	126.69	82.96	55.99	42.07	35.63	32.85
50	144.71	102.5	70.29	50.61	40.11	35.01
60	158.31	120.55	86.01	61.47	46.58	38.48
70	169.21	136.54	102.05	74.08	55.01	43.49
80	177.29	150.1	117.51	87.74	65.14	50.12
90	181.8	160.85	131.64	101.7	76.57	58.29
105	185.86	169.41	144.09	115.33	88.81	67.79
110	189.9	176.4	154.83	128.14	101.33	78.32
120	192.15	181.82	163.87	139.83	113.69	89.51

TABLE 8.2.1 (b) : MODELLED RESULTS FOR COOLING (CASE 4)

	Temperature of the bed, °C					
Time,min	T1M	T2M	T3M	T4M	T5M	T6M
0	184	159	130	100	78	55
10	154.21	158.99	139.81	112.94	89.12	65.94
20	124.55	149.88	144.02	123.32	100.07	76.89
30	101.14	135.7	142.52	130.13	109.86	87.51
40	84.09	119.89	136.35	132.93	117.61	97.3
50	71.03	104.42	126.96	131.85	122.68	105.68
60	61.31	90.43	115.79	127.47	124.81	112.17
70	54.11	78.43	104.08	120.59	124.08	116.44
80	48.77	68.49	92.7	112.09	120.81	118.33
90	44.9	60.49	82.25	102.79	115.52	117.93
105	41.85	54.13	73	93.35	108.79	115.47
110	39.49	49.1	65.07	84.26	101.18	111.29
120	37.73	45.18	58.41	75.86	93.19	105.81

TABLE 8.2.2(a) : MODELLED RESULTS FOR HEATING (CASE 5)

	Temperatures of the bed, °C				
Time, min	T1M	T2M	T3M	T4M	T5M
0	35	32	32	32	32
10	55	36.34	32.82	32.16	32.03
20	82.51	46.26	35.59	32.85	32.19
30	109.59	61.06	41.19	34.62	32.7
40	131.85	78.73	49.89	38.01	33.85
50	149.42	97.29	61.37	43.41	35.98
60	163.62	115.35	74.94	50.93	39.42
70	174.61	131.95	89.71	60.45	44.39
80	183.11	146.62	104.85	71.64	50.99
90	189.73	159.2	119.63	84.01	59.16
100	194.43	169.67	133.51	97.03	68.73
110	197.17	178.05	146.1	110.18	79.38
120	198.76	184.52	157.16	122.98	90.78

TABLE 8.2.2(b): MODELLED RESULTS FOR COOLING (CASE 5)

	Temperatures of the bed, °C				
Time, min	T1M	T2M	T3M	T4M	T5M
0	187	163	131	98	74
10	159.72	164.17	141.61	111.21	84.94
20	130.84	156.83	147.48	122.54	96.07
30	107.53	144.07	148.06	130.98	106.61
40	89.98	128.96	143.9	135.89	115.72
50	77	113.72	136.13	137.11	122.71
60	67.47	99.69	126.1	134.92	127.12
70	59.48	87.24	114.97	129.91	128.8
80	52.78	76.44	103.62	122.8	127.85
90	48.11	67.43	92.74	114.33	124.58
100	44.17	59.97	82.73	105.18	119.43
110	41.5	53.98	73.83	95.92	112.9
120	39.55	49.26	66.12	86.97	105.48

TABLE 8.4.1: HEAT ABSORBED BY THE BED DURING HEATING (CASE 1)

	Heat absorbed by the bed sections, kj							
Time,min	sec-1	sec-2	sec-3	sec-4	sec-5	sec-6	Q_{sum}, kj	Q_{total}, kj
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	76.11	7.61	1.52	0.76	0.00	0.00	86.00	86.00
20	93.61	27.40	6.09	0.00	0.00	0.00	127.10	213.10
33	94.37	60.13	19.03	3.04	0.00	0.00	176.57	389.67
45	76.87	76.11	42.62	17.50	1.52	0.00	214.62	604.30
55	39.58	45.66	31.20	14.46	3.81	1.52	136.23	740.53
60	25.88	25.88	22.07	11.42	2.28	0.00	87.52	828.06
70	41.86	47.19	41.10	26.64	25.12	5.33	187.23	1015.28
80	32.73	39.58	34.25	25.88	16.74	3.81	152.98	1168.26
90	35.01	39.58	44.14	36.53	25.88	14.46	195.60	1363.86
100	22.83	29.68	31.97	28.16	22.07	9.89	144.61	1508.46
110	22.07	33.49	36.53	35.01	29.68	22.07	178.85	1687.32
120	18.27	27.40	28.92	28.16	23.59	15.22	141.56	1828.88
130	15.98	21.31	30.44	30.44	29.68	20.55	148.41	1977.29
140	13.70	19.03	19.79	27.40	19.79	20.55	120.25	2097.54
150	9.13	17.50	20.55	22.83	26.64	24.35	121.01	2218.55
160	8.37	15.22	19.79	21.31	19.79	18.27	102.75	2321.30
170	12.94	14.46	19.03	21.31	19.79	21.31	108.83	2430.13
180	4.57	5.33	10.66	15.22	18.27	16.74	70.78	2500.91
190	9.13	12.18	15.98	21.31	23.59	24.35	106.55	2607.46
200	5.33	11.42	11.42	12.18	12.94	14.46	67.74	2675.20
210	4.57	4.57	10.66	15.22	15.98	18.27	69.26	2744.46
220	4.57	6.85	8.37	10.66	16.74	18.27	65.45	2809.91
230	1.52	6.85	10.66	13.70	12.18	15.22	60.13	2870.04
240	7.61	7.61	7.61	9.89	7.61	9.13	49.47	2919.51
250	1.52	3.81	4.57	6.85	11.42	12.94	41.10	2960.61
260	2.28	4.57	7.61	7.61	9.13	12.94	44.14	3004.75
270	0.76	2.28	-0.76	3.81	6.85	8.37	21.31	3026.06
280	5.33	3.81	9.13	9.13	8.37	12.18	47.95	3074.01
290	0.76	4.57	1.52	5.33	10.66	12.18	35.01	3109.02
300	3.04	1.52	4.57	5.33	3.81	5.33	23.59	3132.61
310	1.52	1.52	1.52	0.76	3.81	6.85	15.98	3148.59
320	0.00	3.81	0.76	4.57	2.28	4.57	15.98	3164.58
330	0.76	0.00	2.28	2.28	7.61	6.85	19.79	3184.36
340	1.52	2.28	5.33	5.33	3.81	4.57	22.83	3207.20

APPENDIX - 2

```
*******************************************************************************
*
*   A PROGRAM FOR SIMULATION OF A PEBBLE BED HEAT REGENERATOR
*
*
*
*******************************************************************************
*   VARIABLE IDENTIFICATION:
*
*   DI       : INNER DIAMETER OF THE COLUMN, in
*   DELTM    : DIFFERNTIAL TIME INTERVAL, min
*   DELTMS   : DIFFERNTIAL TIME INTERVAL, seconds
*   DELZ     : DIFFERENTIAL HEIGHT, in
*   DIAP     : DIAMETER OF THE PEBBLES, in
*   DS       : DENSITY OF THE PEBBLES, kg/m^3
*   CPS      : SPECIFIC HEAT OF THE PEBBLES, kj/kg.K
*   AS       : SURFACE AREA OF PEBBLES PER UNIT VOLUME OF THE COLUMN
*   PHAI     : POROSITY OF THE BED
*   AFM      : AIR FLOW RATE, litres/min
*   WS       : WEIGHT OF THE PEBBLES,kg
*   DA       : DENSITY OF AIR, kg/m^3
*   CPA      : SPECIFIC HEAT OF AIR, kj/kg.K
*   HAIM     : CONVECTIVE HEAT TRANSFER CO-EFFICIENT, Btu/lb.ft^2.oF
*   TA       : TEMPERATURE OF THE AIR, oC
*   TP       : TEMPERATURE OF THE PEBBLES, oC
*
*******************************************************************************
*
*
      DIMENSION TA(0:20,0:20),TP(0:20,0:20)
      REAL DI,DELTM,DELZ,DIAP,DS,CPS,PHAI,AFM,DA,CPA,
     +HAI,DIM,S,AS,DELZM,WS,DELTMS,HAIM,AFS,AMS,CM,A,B,
     +CN,C,D,TA,TP
      OPEN(6,FILE='IN521.DAT',STATUS='UNKNOWN')
      OPEN(8,FILE='OUT521.OUT',STATUS='UNKNOWN')
      READ(6,*) DI,DELTM,DELZ,DIAP,DS,CPS,PHAI,AFM,DA,
     +      CPA,HAI
      DO 10 I=0,12
      READ(6,*) TA(0,I)
   10 CONTINUE
      DO 20 J=0,11
      READ(6,*)TP(J,0)
   20 CONTINUE
      DIM=(DI/12.0)*0.3048
      S=((22/7.0)/4.0)*(DIM**2.0)
      AS=6.0*(1-PHAI)/((DIAP/12.0)*0.3048)
      DELZM=(DELZ/12.0)*0.3048
      WS=S*DELZM*(1-PHAI)*DS
      DELTMS=DELTM*60
      HAIM=HAI*5.678*0.001
      AFS=(AFM*0.001)/60.0
      AMS=AFS*DA
      CM=(AMS*CPA)/(HAIM*DELZM*S*AS)
      A=(2*CM-1.0)/(2*CM+1.0)
      B=2.0/(1.0+2*CM)
      CN=(WS*CPS)/(AMS*CPA*DELTMS)
      C=(CN*(2*CM+1)-2.0)/(CN*(1.0+2*CM))
      D=2.0/(CN*(2*CM+1))
      DO 30 N=0,12
      DO 40 M=0,11
      TA(M+1,N)=A*TA(M,N)+B*TP(M,N)
      TP(M,N+1)=C*TP(M,N)+D*TA(M,N)
   40 CONTINUE
   30 CONTINUE
      DO 50 N=0,12
      WRITE(8,11)(TA(L,N),L=0,11)
   11 FORMAT(1X,13F10.2)
   50 CONTINUE
      WRITE(8,14)A,B,C,D,CM,CN
   14 FORMAT(1X,8F8.2,///,'MODELLED TEMPERATURES OF THE BED, TP')
      DO 60 M=0,12
      WRITE(8,12) (TP(I,M),I=0,11)
```

```
12 FORMAT(1X,13F10.2)
60 CONTINUE
  CLOSE(6)
  CLOSE(8)
  STOP
  END
```