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HSE CONTRACT RESEARCH REPORT No. 122/1996

STUDY OF UPWARD FLAME SPREAD ON INCLINED SURFACES

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This report describes work carried out in the Unit of Fire Safety Engineering, University of Edinburgh, into the mechanism of the rapid fire growth which occurred during the escalator fire at the King's Cross Underground Station on 18th November 1987. This has come to be known as the "trench effect". The approach to the problem involved both an experimental investigation and CFD analysis using FLOW3D. Experimentally, four factors were identified as important parameters for the occurrence of the effect: (i) the slope of the trench; (ii) the geometrical profile of the cross section of the trench; (iii) the nature of the combustible material from which the trench has been constructed; and (iv) the ignition source. A series of experiments designed to examine the influence of the first two factors separately was carried out: this also provided data to test the validity of the CFD simulations. The inclination angle was varied between 10 and 30 degrees. The movement of the buoyant flow in the vicinity of the heat source was simulated and the results compared with the experimental data. The agreement was very satisfactory. Both the experiments and the CFD simulations showed there to be a critical angle for the "trench effect" to occur. The results of both the experiments and the CFD simulations are summarised in this report.

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Contents

Project Report to HSE

Upward Flame Spread On Inclined Surfaces

by

Yajue Wu* and D.D. Drysdale+

Summary

This report describes the work carried out at the Fire Safety Engineering Unit of Edinburgh University on the study of the mechanism of the "trench effect" which was identified as being responsible for the very rapid fire growth during the King's Cross fire of 18th November 1987. Four factors have been identified as important parameters for the occurrence of the 'trench effect': the slope of the trench; the trench geometrical profile; the combustible constructional material and the fire ignition source. The approach to the problem was both by experimental investigation and by using a CFD method. A series of designed experiments were carried out to examine the influence of each relevant factor on the flame behaviour independently, and to provide data for the validation of the CFD simulations. The trench inclination angle varied between 10 and 30 degrees. The movement of the buoyant flow in the vicinity of the heat source was simulated by using the flow modelling package FLOW3D. The results of the simulation have been compared with experiments with good agreement. Both the experiments and the CFD simulations showed that there is a critical trench inclination angle for the 'Trench Effect' to occur. The results of the experiments and CFD simulations are summarised in this report.

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1. Introduction and Background

The fire at the London King's Cross Underground Station on 18 November 1987 demonstrated the ability of fire to spread rapidly up an inclined wooden escalator. Investigations into this fire disaster revealed that this fast fire growth on the escalator was caused by a phenomenon subsequently named the 'trench effect' [1,2]. This phenomenon had the effect of confining and concentrating the flames and combustion products within the trench of the escalator, i.e. below the level of the handrail, preheating the wood ahead, and resulting in the rapid spread of flames up the escalator steps and into the booking hall at the top. This investigation led to the realisation of the certain existence of similar hazardous conditions posed by other inclined channels of combustible material to be found both in industrial situations as well as other public places. A full assessment of any hazard of this kind requires a thorough understanding of the mechanisms involved, and of the importance of all the relevant variables.

As part of the Health & Safety Executives (HSE) investigation into the disaster of November 1987, a preliminary three-dimensional simulation of the gas flows in the escalator shaft and booking hall was carried out by AERE Harwell [3] using the flow modelling package FLOW3D. The results of this simulation showed the attachment of the hot gas to the base of the escalator floor, and first drew attention to the 'trench effect'. As a result of this initial computational fluid dynamics (CFD) simulation, the Buxton laboratories of the HSE [4,5] carried out a series of one-third scale escalator model fire tests, together with smaller scale open channel experiments and ultimately the existence of this 'trench effect' was confirmed experimentally. However at that time because of the urgency of the disaster investigation it was not possible to carry out further work on a more detailed CFD simulation and experimental study, in order to examine the essential conditions for the "trench effect" to occur. Initial small scale experiments at Edinburgh into flame spread on inclined surfaces [6] showed clearly that a change in the flame dynamics occurred at a critical angle of inclination which was responsible for an increased rate of propagation. This project described in this report was proposed after the HSE's initial investigations and aimed at obtaining a thorough understanding of the 'trench effect' and in particular to identify if possible the dependence of the rate of flame spread on relevant parameters such as the trench angle of inclination; the trench geometrical profile; the combustible constructional materials and the conditions of the fire ignition source.

The work was sponsored by HSE, and carried out by Dr Yajue Wu of Edinburgh University with Dr. D.D. Drysdale of Edinburgh University as principal investigator. Drs. S. Jagger, G. Atkinson and C. Lea at the Fire and Thermofluids Section of the HSE Buxton Laboratory were also involved in the project. Officially, the project started on 1st March

1992, when Dr Y. Wu was appointed as a post-doctoral research fellow. The first initial three months were spent in the laboratory of the Fire and Thermofluids Section at Buxton study and becoming familiar with the HARWELL-FLOW3D flow modelling computer software. However the project was interrupted and held back by a more urgent request from the Health and Safety Executive and Eurotunnel Ltd, to undertake an investigation into the behaviour of the fire and smoke of wagon fires burning in the new Channel Tunnel. Consequently, Dr Wu was seconded to the Fire and Thermofluids Section HSE Buxton from June 1992 to September 1993, and worked full time for the project "Interim Validation of Tunnel Fire Consequence Models, Project R.04.33". Dr Wu returned to Edinburgh University in October 1993 and continued the work from October 1993 until 31st August 1994 when Dr. Wu took up a lectureship at Sheffield University. This report describes the work performed during these 11 months. At this stage, much remained to be done, but a new post-doctoral fellow (Dr P. Woodburn) was appointed in January 1995 to continue the work.

2. The Approach

The work differed from the initial incident investigation carried out by HSE and AERE Harwell in 1988, which was mainly aimed at identifying the mechanism of the underground fire. This research project is concerned with a more fundamental study of the mechanism of the specific phenomenon known now as - the 'trench effect'. Four factors are considered to be important parameters for the occurrence of the 'trench effect': the slope of the trench; the trench geometrical profile, the nature of the combustible lining material in the "trench", and the nature of the ignition process. One of the objectives of this project was to examine the influence of each factor on the flame behaviour independently. The approach to the problem was both by experimental investigation and by using a CFD method.

2.1. The Experimental Approach

Two series of experiments were carried out. The first series of experiments was a preliminary study of the 'trench effect' using soft plywood in 1.5 metre length trenches. The preliminary experimental results provided useful information and suggestions for further experimental study. A series of designed experiments was then carried out which were intended to examine the influence of each relevant factor on the flame behaviour independently, as well as to provide data to check against the CFD simulations. This report summarises the results of these two series of experiments.

2.2 The CFD Simulation

It was recognised from the early experimental work that the flow pattern of the hot buoyant gas in the vicinity of the flame played an important role for the 'trench effect' to occur. Therefore in the first stage of the theoretical study, the CFD simulation was aimed at modelling the buoyant flow movement in the vicinity of the heat source by using the time dependent three-dimensional FLOW3D package. The results of the simulation were then compared with the experimental results obtained under the corresponding similar conditions. At this stage, the whole combustion process has not been considered in the CFD simulations. Later it is intended that the combustion model will be used to predict in more detail the flame behaviour in the inclined trenches in the second stage of the CFD simulations. This report will present the results obtained in the first stage of the theoretical work.

3. The Preliminary Experimental Studies Using the Wooden Trenches.

A total of 16 tests aimed at observing the 'trench effect' were carried out in the fire laboratory at Edinburgh University in April 1994. The trenches used in the tests had a geometry of 100 mm in width 100 mm in height and 1500 mm long, and were constructed from 12 mm. soft plywood. The trenches were inclined at various angles to the horizontal, and set alight by the ignition of a small amount of a fuel mixture comprising sawdust, PMMA pellets and paraffin placed across the base of the trench, 50 mm from the lower end. The subsequent fire development after ignition was observed and recorded by using a camera. A total of 16 thermocouples were set up to measure the gas temperatures along the trench as the fire progressed up the trenches.

A separate report on this series of tests has already been sent to the HSE [7]. The main conclusions may be summarised as follows:

1. <u>Trench Inclination Angle:</u>
   The experimental results showed that the pattern of the fire spread inside the trench is affected greatly by changing the trench inclination angle. There was a critical inclination angle for the 'trench effect' to occur. This was approximately 26° for the trench effect to occur in these experiments.

2. <u>Fire Size:</u>
   One of the essential requirements for the 'trench effect' to occur in the trench was that the ignition fuel strip should be spread across the full width of the trench. However there was no evidence to show that the rate of the heat output from the ignition fire source had any obvious influence on the occurrence of the 'trench effect', although a

minimum amount of fuel was required to ignite the plywood and establish sustained fire growth.

3. Trench Material:

Although plywood was used in all the tests, these fall into two groups, (a) that in which "old" material, which had been stored in the laboratory for several months, was used and (b) that in which freshly purchased plywood (of the same type and density) was used. The latter was more difficult to ignite, requiring a larger ignition source, and self-extinguished after a short period. However, the mechanism of the "trench effect" was observed (i.e. the flames lay down in the trench) for inclinations greater than 26^{o}. No further study of the effect of the lining material was possible in the time available.

4. Trench Geometrical Profile:

The influence of the trench geometrical profile was not explored in this particular series of tests.

4. The Experimental Studies by Using Gas Burner

The experimental results from the wooden trench tests clearly indicated that the inclination angle is one of the most important parameters relating to the occurrence of the 'trench effect'. There is a critical inclination angle for the fast fire spread phenomenon to be produced in the trench. The experimental results also showed that the actual combustion processes on the surfaces of the wooden trench are very complicated. Further study to assess the influence of the parameters independently using wooden trenches was considered too difficult, particularly as there is no control over the rate of release of the flammable volatile from the fuel.

To allow a more systematic examination of the dynamics of the flame and hot combustion gases in the trench, a more controllable "fire" was developed for further experimental work. This technique allowed the relevant parameters to be better controlled during the tests, and (in principle) would allow the influence of the various factors to be assessed independently. This would also permit more accurate and more consistent data on the heat release rate from the fire to be obtained for the CFD simulations. A gas burner was constructed from a flat perforated steel plate and used as a fire model in the second series of experiments.

It would appear that the principal reason for rapid fire spread up an inclined trench is that the rate of heating of the combustible material ahead of the pyrolysis zone is greatly increased by the characteristics of the flow of combustion gases within the trench. Therefore the behaviour of the hot buoyant gases produced by a flame burning in the trench is of great significance in producing the phenomenon of the 'trench effect'. This was examined in the second series of tests using trenches constructed of non-combustible material (Monolux board) with the perforated plate burner located on the base of the trench, near the lower end (see Figure 1). The study was focused on observations of the movement of the hot combustion products arising from a flame burning at the plate for various angles of inclination, heat release rate and cross section dimensions of the trench.. In this way, the essential conditions for the occurrence of the 'trench effect' were examined.

4.1 The Apparatus

The test trench was constructed using 12 mm thickness Monolux board supported by a steel frame whose angle of inclination could be varied from 0° to 30° to the horizontal. The perforated plate burner was of the same width as the trench and was fitted flush with the trench floor, 138 mm from the trench base. The length of the burner was 92 mm. The burner was supplied with propane gas through a flowmeter which allowed the heat release rate to be controlled. Two types of flames could be generated by the burner. At very low propane flowrates, a uniform, blue, premixed-like flame was sustained immediately above the burner surface. Under these conditions, the combustion of propane and air was completed close to the burner, thus providing simply a source of hot buoyant gas: otherwise, no combustion took place in the trench. Therefore the movement of buoyant gas could be examined. When the propane flowrate was increased, a yellow diffusion flame was generated across the full width of the trench. The behaviour of the flame and the movement of the hot combustion products could then be studied. Figure 1 shows a simplified schematic diagram of the trench which was set up inside a special experimental facility and screened by thin gauze sheets to prevent any disturbance from extraneous draughts in the laboratory.

4.2 The Experimental Measurements

K-type thermocouples were used to measure the gas temperatures along the trench. Their specification was to IEC 584-2:1982, class 2 standard. This gave a possible error of 2.5 °C or 0.75% of the actual temperature whichever is greater. A Microlink data logging system combining a 386 PC was used to record the experimental data. During each test, the propane flowrate was kept constant, the data acquisition started when the propane flowrate became stable, and steady state conditions for the flame and buoyant flow was obtained. The data were sampled at half second intervals over a period of 2 minutes. The results of the temperature measurements are presented later in Appendix A. In some experiments, the static pressure and total pressure at a number of locations were measured by using pressure transducers in order to obtain velocity data. This part of work was aimed at a study of the transient flow structure of the combustion products along the trench. The interpretation of these data did not form part of the current project, but will be discussed in a future report [8].

4.3 The Experimental Results

The conditions of the tests carried out are summarised in Table 1.

In order to examine the influence of effect of dimensions, two different sizes of trenches were constructed. The smaller trench was 2438 mm long and 92 mm wide with side-walls 92 mm high. The larger trench was 2438 mm long, 276 mm wide and 276 mm high. A few additional tests were carried out with the larger trench, but with different lengths, and heights. Table 1 lists the trench sizes for each test.

The experimental data are presented in the tables and graphs in Appendix A.

Table 1 indicates the table and figure numbers where the experimental data are presented for each test. The locations of the thermocouples are given in each table. An xyz coordinate plot was set up and is shown in Figure 1.

4.4 Discussion

<u>**Tests 1-5**</u>

The experimental results obtained from the second series of tests showed that the movement of the buoyant gases resulting from the flame was strongly depended on the trench inclination angle. Tests 1 to 5 were conducted to assess the influence of the angle of inclination. In this set of tests, the trench inclination was varied from 15° to 30° to the horizontal, and all other parameters were kept the same. The larger trench was employed, and the propane flowrate to the gas burner was maintained at 6 litres/minute, generating a 9.9 kW diffusion flame approximately 300 mm long.

When the trench inclination angle was at 15°, it was observed that close to the burner, the flame appeared to be attached the trench floor, but then lifted up, the buoyant gases forming a near-vertical plume which rose out the trench towards the ceiling of the rig. The temperature distribution inside the trench is showed in Figure A1. The temperature at the top of the trench indicated that the hot gases had left from the trench about 125 mm away from the burner front. The temperature inside the trench 500 mm from the burner towards the top end of the trench was ambient This indicated that no hot buoyant gases had progressed up inside the trench at all. There was no evidence for the 'trench effect' in this test.

In test 2 the inclination angle was increased to 17°, it was observed that the flame itself appeared to lie down and attach to the floor of the trench, but the buoyant plume still lifted out of the trench almost vertically. The temperature distribution shown in Figure A2 indicated that the buoyant gases exited from the trench at a distance about 500 mm away from the front edge of the burner. From a point halfway away (1000 mm.) from the burner up to the top end of the trench, the temperature inside the trench was equal to ambient beyond 1000 mm above the burner. The 'trench effect' did not occur in this test either.

Figure A3 shows the temperature distribution inside the trench when the trench inclination angle was increased to 19°. In this test, the flame and the buoyant gases behaved in a similar way to test 2 shown in Figure A2 in which the trench inclination angle was at 17°. The 'trench effect' did not occur in this test.

However when the inclination angle was increased to 21° in test 4, it was observed that the behaviour of the hot buoyant gases changed dramatically. It was found that the main stream of the hot buoyant gases flowed inside the trench, eventually exiting from the upper end. There are two distinct sections in the temperature distribution shown in Figure A4. In the section between the front edge of the burner and a point 500 mm away from the burner up the trench, the temperature measured along the height of the trench was highly stratified. The temperature at the top of the trench (270 mm above the trench floor) was at the room temperature, the temperature at the centre of the trench (140 mm above the trench floor) was just above room temperature, and at the bottom of the trench (10 mm above the trench floor), a much higher temperature was detected. The temperature stratification in this section indicated that the hot buoyant gases were fully confined inside the trench and were located in the lower part of the trench near the trench floor. This kind of temperature stratification disappeared about 1000 mm from the burner, and the cross-sectional temperature inside the trench became uniform, and the overall temperature of the cross-section then gradually reduced along the trench. At the top end of the trench, the overall temperature was uniform, but higher than the room temperature. These features of the temperature distribution in this section indicated that as the buoyant gases progressed up the trench, fresh air was entrained and mixed with the buoyant gases, giving a uniform mixture over the full cross section of the trench. As a result, the buoyant gases may not be fully confined inside the trench.

The experimental results clearly showed that the critical inclination angle for the large trench lay between 19° and 20°. The features of the buoyant gas movement clearly indicated that the 'trench effect' occurred in this test.

A similar movement of the buoyant gases was observed in test 5 in which the trench inclination angle was set up at 30°, the temperature distribution along the trench is shown in Figure A5. The 'trench effect' clearly occurred in this test.

Tests 6-9

To examine the influence of the heat release rate on the critical inclination angle, tests 6-9 were carried out at trench inclinations from 17° to 30°, but the propane flowrate was increased to 11 litres/minute, corresponding to a 18.2 kW flame. It was observed that the flame attached to the trench floor in all four tests, and the flame length measured was about 500 mm. The temperature distributions obtained in these four tests are shown in Figures A6-A9. These indicate clearly that the critical inclination angle is not influenced by increasing the heat release rate from the fire. The critical inclination angle for the trench effect to occur was still the same, at 21°.

Tests 10-11

In the tests 10 and 11, the gas burner was used solely as a heat source, so that the movement of the buoyant gas resulting from this heat source could be studied. The propane flowrate was set up at 1 litre/minute, the heat release rate from the flame was at 1.65 kW. In this condition the flame could be considered as a source of hot gas. Therefore the temperature distribution obtained in these tests, shown in Figures A10 and A11, reflected only the movement of the buoyant gases resulting from the heat source.

In test 10, the trench inclination angle was at 15°. The temperature distribution inside the trench shown in Figure A10 indicated that the buoyant gases moved vertically out the trench.

In test 11, the trench inclination angle was set at 30°. The temperature distribution inside the trench was very similar to the one obtained in the test 5. It could be divided into two sections: a stratified temperature section and a uniform temperature section. The 'trench effect' was observed in this test.

Tests 12-17

To assess the influence of the heat output rate from the flame on the movement of the buoyant gases, the tests 12-14 were carried out at the trench inclination angle of 15°, but the heat output rate from the flame was varied at 1.65 kW, 9.9 kW and 18.2 kW. This sequence of experiments were repeated at an inclination angle of 30°, as tests 15-17. The temperature data obtained are presented in Figures A12 A17 There was no evidence to show that the heat release rate of the fire had any obvious influence on the flame pattern and the movement of the buoyant flow. However, the temperature of the buoyant gases inside the trench and also the temperature of the gases exiting from the top end of the trench were both increased as the heat release rate increased.

Tests 18-21

The tests 18 and 19 were carried out at the inclination angle of 22°. The inclination angle was increased to 24° in the test 20, and to 26° in the test 21. The movement of the buoyant gases observed in these tests was similar to that the tests 4 and 11. The 'trench effect' was observed in these tests.

Tests 22-30

These tests were aimed at obtaining the detailed temperature distribution inside the trench. The trench inclination was kept at 30°, and the heat release rate varied at 1.65 kW, 9.9 kW and 18.2 kW. Figures A21-A47 present the temperature distribution inside the trench. The tests provided valuable information for the CFD simulations.

Tests 31-36

This series of tests were carried out in the smaller trench (2438 mm length, 92 mm height and 92 mm width), and were aimed at examining the influence of the scale of the trench. The smaller trench had the same length as the large trench, but it was one third the scale of the large trench in cross-section. The trench inclination angle was set up at 30°, the three heat release rates were used, 3.3 kW, 9.9 kW and 18.2 kW. The temperature distribution inside the trench was plotted in Figures A48 -A53. In these tests, it was observed that the flame was confined inside the trench and attached to the floor of the trench. The hot buoyant gases reached the top end of the trench. However, in the flame zone, the thickness of the flame was of the same magnitude as the height of the trench sidewalls, the flame almost occupied the full cross section of the trench. It is shown in Figure A50 that the thickness of the flame was greater than the half height of the trench, when the heat release rate was increased to 9.9 kW. In Figure A52, it is shown that the flame almost occupied the whole cross-section of the trench when the heat release rate from the flame reached 18.2 kW. The temperature distribution can also be divided into stratification and non-stratification sections. The behaviour of the flame and the movement of the buoyant gases were very similar to the tests in the large trench.

To assess the scaling effect, the test 31 shown in Figure 48 may be considered as the one-third scale experiment of the test 5 shown in Figure 5. Comparing Figures 5 and 48, it can be seen that the features of the temperature distribution inside the trench were very similar.

Test 37

By varying the trench inclination angle and the heat release rate from the flame, it was shown that the critical inclination angle for the 'trench effect' to occur in this smaller trench was about 26°, however the critical inclination angle was not influenced by the heat release rate from the flame. Comparing this with the critical angle for the large trench, it was shown that the critical angle for the "trench effect" to occur was mostly determined by the geometrical parameters of the trench.

Tests 38 -42

To examine the influence of the sidewalls of the trench, a series of tests were carried out using the trench construction based on the large trench of 276 mm width, but with the height of the side-wall being reduced systematically. The experimental results showed that there was no obvious change in the flame behaviour when the height of the side-wall was reduced. Even when the sidewalls were removed completely, the flame still appeared to attach to the 'trench' floor. The flame front started to lift away from the floor when the inclination was reduced, equal to or less than 15°. However, the movement of the buoyant gas resulting from the flame was influenced by reduction of the height of the sidewalls. When the height of the sidewalls was halved and the inclination angle was less than 25° the buoyant gases lifted out of the trench.

5. CFD Simulation

The time dependent three-dimensional FLOW3D package was used to simulate the movement of the buoyant flow in the vicinity of the heat source. The results of the simulation were compared with the experimental results under the corresponding conditions.

5.1. Geometrical Representation

Considering the features of the experimental set up, the aerodynamic conditions surrounding the trench were obviously important regarding the buoyant flow movement near the heat source. In order to avoid setting up any arbitrary boundary conditions near the trench in the

CFD simulations, several computational domains were examined and it was decided that the best way to set up the computational geometry was to imagine that the trench was placed at the centre of an arbitrary room of 3m height x 3m width x 4.43m length, as shown in Figure 2.

5.2 Grid Generation

In order to save computational time, it was assumed that the flow inside the trench was symmetrical, and a symmetrical plane was set up at plane $z = 0$. The FLOW3D multi-block finite-difference grid was used. The computational domain comprised 12 blocks. The trench was set up as a block, with a 53x20x10 grid being generated in the trench block. Large grids were used in the room zone. Figure B1 in the Appendix B shows a view of the surface of the grid at the symmetrical plane $z = 0$. The mesh at the plane $y = 0$, where the trench base is located is shown in Figure B2.

5.3 Boundary Conditions

The thin adiabatic wall boundary conditions were set up to represent the trench wall surfaces. In order to minimise the influence of boundary conditions, wall boundary conditions were set up on the surfaces of the arbitrary room walls, and pressure boundary conditions were set up only on the surface of the arbitrary room floor.

5.4. Mathematical Modelling and Computational Details

In FLOW3D, buoyant flows can be modelled in one of two ways. Either, the flow can be treated as compressible, with the gas density given by an equation of state, or, the flow can be modelled using the Boussinseq approximation. In the series of experiments, the heat release rate from the burner was very small and the temperature difference in the flow was small, therefore the Boussinseq approximation was used to model the buoyant flow. During the CFD simulation, the computational geometry was kept unchanged, and variation of the trench inclination angle was achieved by varying the gravity direction. USER FORTRAN USRSRC was used to set up the heat release rate on the surface of the burner. The heat release rate was 6.5 kW/m^2. The computation was time dependent.

5.5. Results

The simulation was carried out at the inclination angles of 30°, 20°, 15° and 10°. The results showed that the pattern of the buoyant flow changed when the inclination angle was reduced. Figure B3 shows the temperature contours at the symmetrical plane when the inclination angle is 30° at the time step of 20s. It shows that the hot buoyant gas flow moves up the trench parallel to the trench floor, and attaches itself to the trench floor. Figure B4 shows the temperature contours at the time step of 20 seconds when the inclination angle was reduced to 20°. The buoyant flow is attached to the trench floor, but the front head of the buoyant flow rises up. This indicates that the buoyant flow pattern inside the trench changes at the inclination angle of 20°. When the inclination angle is reduced to 15°, the temperature contours as shown in Figure B5 indicate that the buoyant flow rises out of the trench. The buoyant flow rises almost vertically when the inclination angle is reduced to 10° as shown in Figure B6, and there is little or no flow up the inside of the trench.

The results of the CFD simulations showed that the dominant feature of the movement of buoyant flow is its attachment to the trench floor, when the trench inclination angle is greater than 20°. This kind of attachment does not occur inside the trench when the inclination is less than 20°. The critical inclination angle for this trench therefore is 20°. The same conclusion was obtained from the experimental results.

6. Discussion and Suggestions for the Future Work.

The tendency for the buoyant flow to attach itself to the trench floor is the essential condition for the 'trench effect' to occur. This movement of the hot buoyant flow indicated the trend of possible fire growth in the trench. In order to examine the behaviour of the buoyant flow, the influence of the combustion process and the influence of the constructional material of the trench itself, were not considered in this study. Up to now only the initial buoyant flow movement has been studied. The attachment of the buoyant flow to the trench with the additional combustion of trench material is likely to provide conditions for an enhanced "trench effect" to occur and this will be studied in future work. Further study of flame and combustion product behaviour well ahead of the trench surface combustion front are other tasks to be included in the next stage of CFD simulation.

7. Conclusions

1. The essential conditions for the 'trench effect' are examined by experimental study and CFD simulations of the buoyant gases movement in the inclined trench. The results of both the experiments and the CFD simulation showed that the buoyant flow movement in the inclined trench depended on the trench inclination.

2. There is a critical trench inclination angle for the "trench effect" to occur. The critical inclination angle is about 21° for the large trench (2438 mm L x 276 mm W x 276 mm H), .and 26° for the small trench(2438 mm L x 92 mm W x 92 mm H).

3. The critical trench inclination angle is determined mostly by the trench geometrical profile. The experimental results showed that the rate of heat output from the ignition fire source had no obvious influence on the occurrence of the 'trench effect',

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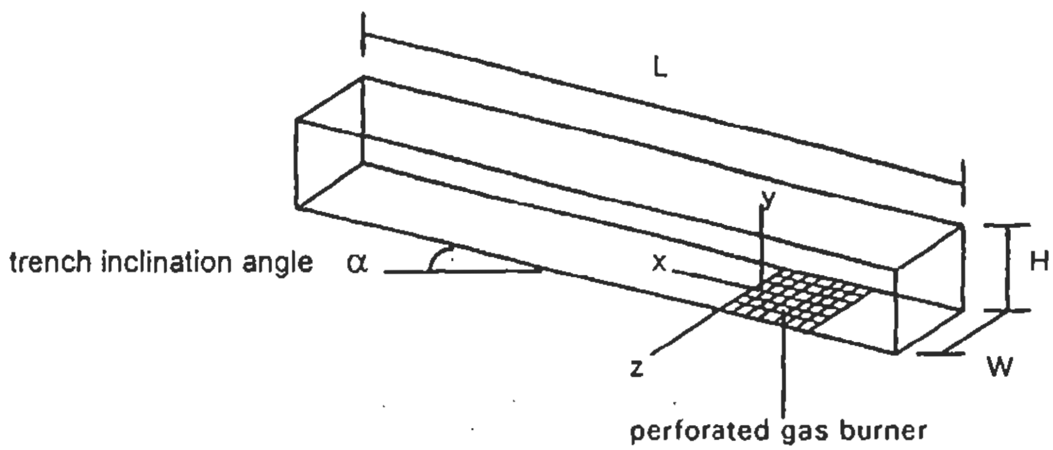


Figure 1. The schematic diagram of the inclined test trench

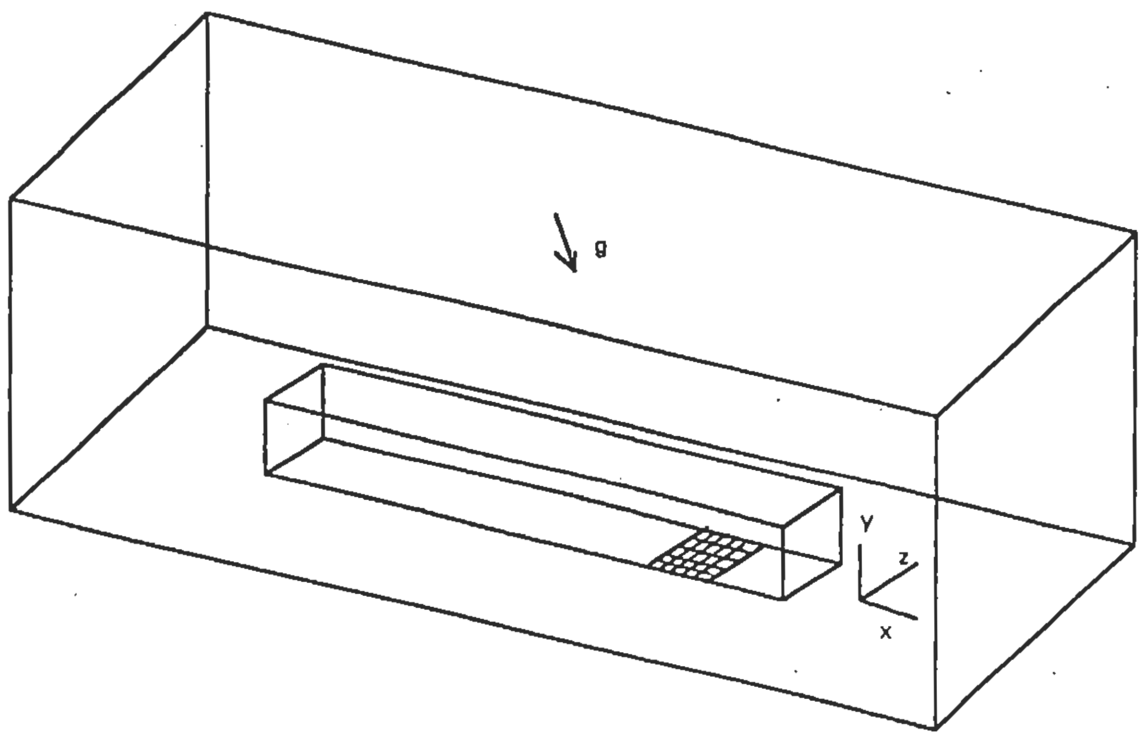


Figure 2. The schematic diagram of the computational geometry.

Table 1: The conditions of tests

Test Number	Trench Geometry LengthxWidthxHeight (mm)	Inclination Angle (Degrees)	Propane Flowrate (Litres/Minute)	Data Presented in Table	Data Presented in Figure
1	2438x276x276	15	6	A1	A1
2	2438x276x276	17	6	A1	A2
3	2438x276x276	19	6	A1	A3
4	2438x276x276	21	6	A1	A4
5	2438x276x276	30	6	A1	A5
6	2438x276x276	17	11	A2	A6
7	2438x276x276	19	11	A2	A7
8	2438x276x276	21	11	A2	A8
9	2438x276x276	30	11	A2	A9
10	2438x276x276	15	1	A3	A10
11	2438x276x276	30	1	A3	A11
12	2438x276x276	15	1	A4	A12,A13,A14
13	2438x276x276	15	6	A4	A12,A13,A14
14	2438x276x276	15	11	A4	A12,A13,A14
15	2438x276x276	30	1	A5	A15.A16,A17
16	2438x276x276	30	6	A5	A15,A16,A17
17	2438x276x276	30	11	A5	A15,A16,A17
18	2438x276x276	22	6	A6	A18
19	2438x276x276	22	11	A6	-
20	2438x276x276	24	6	A7	A19
21	2438x276x276	26	6	A7	A20
22	2438x276x276	30	1	A8	A21,A24,A25,A26,A27,A28,A29
23	2438x276x276	30	1	A8	A22,A24,A25,A26,A27,A28,A29
24	2438x276x276	30	1	A8	A23,A24,A25,A26,A27,A28,A29
25	2438x276x276	30	6	A9	A30,A33,A34,A35,A36,A37,A38
26	2438x276x276	30	6	A9	A31,A33,A34,A35,A36,A37,A38
27	2438x276x276	30	6	A9	A32,A33,A34,A35,A36,A37,A38
28	2438x276x276	30	11	A10	A39,A42,A43,A44,A45,A46,A47
29	2438x276x276	30	11	A10	A40,A42,A43,A44,A45,A46,A47
30	2438x276x276	30	11	A10	A41,A42,A43,A44,A45,A46,A47
31	2438x92x92	30	2	A11	A48
32	2438x92x92	30	2	A11	A49
33	2438x92x92	30	6	A12	A50
34	2438x92x92	30	6	A12	A51
35	2438x92x92	30	11	A13	A52
36	2438x92x92	30	11	A13	A53
37*	2438x92x92	15-30	2-11	-	-
38*	2438x276x138	15-30	6	-	-
39*	2438x276x0	30	6	-	-
40*	1219x276x276	15-30	6	-	-
41*	2438x276x276	10	6	-	-
42*	2438x276x276	0	6	-	-

* No temperature measurement was made in the test. Only visual observation was used.

Appendix A

The Experimental Data

Table A1: Experimental data: Temperature
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 6 litres/minute

Thermocouple Number	Thermocouple's Position (x,y,z) (mm)	15 Temperature °C	17 Temperature °C	19 Temperature °C	21 Temperature °C	30 Temperature °C
		Trench Inclination Angle (°)				
00700	(2168,10,0)	22.7	23.6	22.4	26.4	38.6
00701	(2168,140,0)	19.3	19.6	20.8	42.0	44.6
00702	(2168,270,0)	19.9	19.9	20.5	45.1	42.2
00703	(1100,10,0)	22.7	22.4	21.1	65.7	63.1
00704	(1100,140,0)	22.0	22.0	21.4	72.6	67.3
00705	(1100,270,0)	22.0	22.0	21.4	64.5	55.9
00706	(500,10,0)	27.6	92.8	30.7	85.5	74.9
00707	(500,140,0)	29.4	48.7	27.3	82.2	106.6
00708	(500,270,0)	26.0	97.3	55.4	52.9	37.3
00709	(250,10,0)	64.5	218.3	139.1	238.8	367.5
00710	(250,75,0)	70.2	261.8	216.1	277.6	380.9
00711	(250,140,0)	368.8	192.7	223.9	150.9	136.8
00712	(250,205,0)	140.6	94.0	146.5	62.9	42.2
00713	(250,270,0)	163.6	53.9	86.1	45.1	32.1
00714	(125,10,0)	368.8	445.5	440.7	422.2	604.7
00608	(125,75,0)	389.6	251.0	216.4	233.4	203.5
00609	(125,140,0)	333.6	161.4	145.6	139.6	102.6
00610	(125,205,0)	223.9	90.4	87.3	77.3	48.0
00611	(125,270,0)	162.7	53.9	54.7	51.4	36.4
00613	(0,10,0)	300.0	250.4	187.6	271.8	172.2
00614	(0,140,0)	84.6	62.3	71.6	76.1	47.7
00615	(0,270,0)	46.0	40.2	39.8	43.2	35.5

Table A2: Experimental data: Temperature
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 11 litres/minute

Thermocouple Number	Thermocouple's Position (x,y,z) (mm)	Trench Inclination Angle (°) 17 Temperature °C	19 Temperature °C	21 Temperature °C	30 Temperature °C
00700	(2168,10,0)	23.9	22.7	30.7	48.3
00701	(2168,140,0)	19.6	19.9	63.9	59.5
00702	(2168,270,0)	20.2	20.5	57.8	53.7
00703	(1100,10,0)	24.5	23.3	94.6	83.0
00704	(1100,140,0)	23.9	23.0	103.4	100.5
00705	(1100,270,0)	24.2	23.0	96.4	93.3
00706	(500,10,0)	44.2	38.7	121.6	104.1
00707	(500,140,0)	42.3	38.7	132.6	178.2
00708	(500,270,0)	68.4	56.6	98.5	45.8
00709	(250,10,0)	277.3	290.3	469.6	507.9
00710	(250,75,0)	418.0	419.2	407.4	402.2
00711	(250,140,0)	407.1	379.2	205.2	191.0
00712	(250,205,0)	283.1	266.4	95.2	69.8
00713	(250,270,0)	197.4	167.4	70.2	50.7
00714	(125,10,0)	562.6	552.0	535.9	514.7
00608	(125,75,0)	377.5	264.2	276.3	221.0
00609	(125,140,0)	269.1	198.9	188.6	140.8
00610	(125,205,0)	173.9	138.4	129.5	72.2
00611	(125,270,0)	125.6	100.9	79.7	54.6
00613	(0,10,0)	363.5	266.9	403.8	259.5
00614	(0,140,0)	108.8	110.0	113.9	64.0
00615	(0,270,0)	64.5	62.9	61.4	48.0

Table A3: Experimental data: Temperature
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 1 litre/minute

		Trench Inclination Angle (°)	
		15	30
Thermocouple Number	Thermocouple's Position (x,y,z) (mm)	Temperature °C	Temperature °C
00700	(2168,10,0)	22.3	27.8
00701	(2168,140,0)	18.9	28.1
00702	(2168,270,0)	19.5	28.1
00703	(1100,10,0)	19.8	29.3
00704	(1100,140,0)	19.8	30.2
00705	(1100,270,0)	19.8	28.7
00706	(500,10,0)	20.4	28.4
00707	(500,140,0)	20.1	41.3
00708	(500,270,0)	21.1	19.5
00709	(250,10,0)	36.8	75.2
00710	(250,75,0)	50.5	65.5
00711	(250,140,0)	74.3	22.8
00712	(250,205,0)	63.5	20.4
00713	(250,270,0)	44.4	20.1
00714	(125,10,0)	124.0	75.5
00608	(125,75,0)	66.2	22.2
00609	(125,140,0)	45.6	23.4
00610	(125,205,0)	28.5	20.3
00611	(125,270,0)	25.7	19.1
00613	(0,10,0)	156.7	55.2
00614	(0,140,0)	29.4	22.8
00615	(0,270,0)	23.8	20.0

Table A4: Experimental data: Temperature
Trench size: 2438 mm L x 276 mm W x 276 mm H
Trench inclination angle = 15°

Thermocouple Number	Thermocouple's Position (x,y,z) (mm)	Propane Flowrate (litres/minute) 1 Temperature °C	6 Temperature °C	11 Temperature °C
00700	(962,10,0)	20.4	21.7	22.0
00701	(962,140,0)	20.4	21.7	22.0
00702	(962,270,0)	21.1	22.3	22.3
00612	(708,10,0)	33.0	37.1	38.3
00613	(708,75,0)	19.1	22.0	22.9
00614	(708,140,0)	19.5	22.9	23.5
00615	(708,270,0)	19.1	23.5	24.1
00703	(454,10,0)	20.7	26.6	30.3
00704	(454,75,0)	21.1	26.3	31.5
00705	(454,140,0)	21.1	26.9	33.7
00706	(454,205,0)	21.1	26.9	32.5
00707	(454,270,0)	20.7	26.0	30.9
00708	(200,10,0)	22.0	45.6	63.8
00709	(200,75,0)	22.6	47.1	69.9
00710	(200,140,0)	22.3	45.3	61.4
00711	(200,205,0)	26.9	96.3	108.1
00712	(200,270,0)	48.6	154.2	188.6
00713	(100,10,0)	34.3	114.5	167.9
00714	(100,75,0)	93.9	437.1	371.7
00608	(100,140,0)	146.7	572.8	548.1
00609	(100,205,0)	97.2	417.7	551.4
00610	(100,270,0)	70.7	308.7	438.6
00611	(0,140,0)	29.0	74.0	97.5

Table A4: Experimental data: Temperature
Trench size: 2438 mm L x 276 mm W x 276 mm H
Trench inclination angle = 15°

		Propane Flowrate (litres/minute)		
		1	6	11
Thermocouple Number	Thermocouple's Position (x,y,z) (mm)	Temperature °C	Temperature °C	Temperature °C
00700	(962,10,0)	20.4	21.7	22.0
00701	(962,140,0)	20.4	21.7	22.0
00702	(962,270,0)	21.1	22.3	22.3
00612	(708,10,0)	33.0	37.1	38.3
00613	(708,75,0)	19.1	22.0	22.9
00614	(708,140,0)	19.5	22.9	23.5
00615	(708,270,0)	19.1	23.5	24.1
00703	(454,10,0)	20.7	26.6	30.3
00704	(454,75,0)	21.1	26.3	31.5
00705	(454,140,0)	21.1	26.9	33.7
00706	(454,205,0)	21.1	26.9	32.5
00707	(454,270,0)	20.7	26.0	30.9
00708	(200,10,0)	22.0	45.6	63.8
00709	(200,75,0)	22.6	47.1	69.9
00710	(200,140,0)	22.3	45.3	61.4
00711	(200,205,0)	26.9	96.3	108.1
00712	(200,270,0)	48.6	154.2	188.6
00713	(100,10,0)	34.3	114.5	167.9
00714	(100,75,0)	93.9	437.1	371.7
00608	(100,140,0)	146.7	572.8	548.1
00609	(100,205,0)	97.2	417.7	551.4
00610	(100,270,0)	70.7	308.7	438.6
00611	(0,140,0)	29.0	74.0	97.5

Table A5: Experimental data: Temperature
Trench size: 2438 mm L x 276 mm W x 276 mm H
Trench inclination angle = 30°

Thermocouple Number	Thermocouple's Position (x,y,z) (mm)	Propane Flowrate (litres/minute) 1 Temperature °C	6 Temperature °C	11 Temperature °C
00700	(962,10,0)	35.8	62.6	98.8
00701	(962,140,0)	37.1	81.3	127.4
00702	(962,270,0)	30.3	71.6	105.4
00612	(708,10,0)	59.6	99.4	181.4
00613	(708,75,0)	48.6	94.2	178.6
00614	(708,140,0)	30.3	64.7	99.7
00615	(708,270,0)	24.4	54.4	82.8
00703	(454,10,0)	68.3	189.5	418.6
00704	(454,75,0)	65.6	151.7	288.2
00705	(454,140,0)	37.7	75.5	154.5
00706	(454,205,0)	24.4	37.1	58.6
00707	(454,270,0)	23.8	30.9	43.8
00708	(200,10,0)	111.7	535.2	654.6
00709	(200,75,0)	84.0	217.0	338.7
00710	(200,140,0)	26.6	73.7	147.1
00711	(200,205,0)	27.5	53.2	89.4
00712	(200,270,0)	26.9	42.9	69.2
00713	(100,10,0)	237.8	563.7	641.6
00714	(100,75,0)	79.7	188.6	273.9
00608	(100,140,0)	44.4	109.3	162.0
00609	(100,205,0)	36.2	74.0	116.0
00610	(100,270,0)	28.8	50.8	78.8
00611	(0,140,0)	34.6	58.3	79.7

Table A6: Experimental data: Temperature
Trench size: 2438 mm L x 276 mm W x 276 mm H
Trench inclination angle = 22°

Thermocouple Number	Thermocouple's Position (x,y,z) (mm)	Propane flow rate (litres/minute) 6 Temperature °C	11 Temperature °C
00700	(962,10,0)	32.5	59.9
00701	(962,140,0)	65.4	108.5
00702	(962,270,0)	75.0	117.0
00612	(708,10,0)	94.0	167.3
00613	(708,75,0)	89.5	176.7
00614	(708,140,0)	81.0	110.0
00615	(708,270,0)	73.2	100.9
00703	(454,10,0)	158.0	364.7
00704	(454,75,0)	141.6	311.8
00705	(454,140,0)	86.1	174.9
00706	(454,205,0)	47.8	76.2
00707	(454,270,0)	41.4	60.0
00708	(200,10,0)	457.5	622.2
00709	(200,75,0)	218.3	344.7
00710	(200,140,0)	104.6	188.9
00711	(200,205,0)	66.3	107.3
00712	(200,270,0)	52.3	81.9
00713	(100,10,0)	526.5	638.7
00714	(100,75,0)	214.9	279.7
00608	(100,140,0)	125 6	178 6
00609	(100,205,0)	89 1	128 3
00610	(100,270,0)	63 6	95 5
00611	(0,140 0)	63 6	63 6

Table A7: Experimental data: Temperature
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 6 litres/minute

Thermocouple Number	Thermocouple's Position (x,y,z) (mm)	Trench Inclination Angle (°) 24 Temperature °C	26 Temperature °C
00700	(962,10,0)	54.2	59.9
00701	(962,140,0)	79.8	78.0
00702	(962,270,0)	82.5	74.4
00612	(708,10,0)	100.0	95.5
00613	(708,75,0)	94.9	88.2
00614	(708,140,0)	72.9	65.0
00615	(708,270,0)	69.0	64.1
00703	(454,10,0)	168.0	168.9
00704	(454,75,0)	145.9	143.1
00705	(454,140,0)	79.2	73.5
00706	(454,205,0)	43.8	40.5
00707	(454,270,0)	39.9	36.2
00708	(200,10,0)	513.9	462.8
00709	(200,75,0)	248.9	204.0
00710	(200,140,0)	102.1	82.8
00711	(200,205,0)	64.8	62.3
00712	(200,270,0)	51.7	50.5
00713	(100,10,0)	572.3	467.8
00714	(100,75,0)	211.2	178.3
00608	(100,140,0)	123.4	118.2
00609	(100,205,0)	88.5	83.1
00610	(100,270,0)	61.7	59.9
00611	(0,140,0)	63.6	60.8

Table A8: Experimental data: Temperature
Trench size: 2438 mm L x 276 mm W x 276 mm H
Trench inclination angle = 30°
Propane flow rate = 1 litres/minute

Thermocouple's Number	Thermocouple's Position (x,y)(mm)	Thermocouple's Position (z)(mm) 0 Temperature °C	69 Temperature °C	128 Temperature °C
00700	(2168,10)	30.7	30.2	28.2
00701	(2168,140)	33.5	32.7	30.7
00701	(2168,270)	32.9	31.6	30.0
00703	(1100,10)	36.7	37.7	32.9
00704	(1100,140)	38.5	40.2	37.0
00705	(1100,270)	33.7	35.8	36.0
00708	(500,10)	54.2	57.0	45.2
00709	(500,140)	31.0	37.7	53.0
00710	(500,270)	25.5	28.9	35.0
00711	(125,10)	94.8	76.7	77.9
00712	(125,140)	28.8	31.0	38.9
00713	(125,270)	25.7	26.6	30.4
00714	(0,140)	31.0	31.0	35.5
00608	(0,270)	24.5	24.0	26.8
00609	(-48 140)	32 0	33 9	35 0
00610	(-48,270)	25 0	25 2	25 7
00611	(96 140)	28 8	30 2	31 7
00612	(96 270)	40 0	40 3	40 8

Table A9: Experimental data: Temperature
Trench size: 2438 mm L x 276 mm W x 276 mm H
Trench inclination angle = 30°
Propane flow rate = 6 litres/minute

		Thermocouple's Position (z)(mm)		
		0	69	128
Thermocouple's Number	Thermocouple's Position (x,y)(mm)	Temperature °C	Temperature °C	Temperature °C
00700	(2168,10)	37	41	35
00701	(2168,140)	45	46	41
00701	(2168,270)	43	43	38
00703	(1100,10)	62	63	53
00704	(1100,140)	66	71	67.8
00705	(1100,270)	56	65	60.8
00708	(500,10)	100	112	107.9
00709	(500,140)	65	98	120
00710	(500,270)	39	64	67.8
00711	(125,10)	289	262	250
00712	(125,140)	68	114	104
00713	(125,270)	30	36	45
00714	(0,140)	47	46	48
00608	(0,270)	30	31	30
00609	(-48,140)	50	33	49
00610	(-48,270)	34	33	32
00611	(-96,140)	42	43	40
00612	(-96,270)	49	49	33

Table A10: Experimental data: Temperature
Trench size: 2438 mm L x 276 mm W x 276 mm H
Trench inclination angle = 15°
Propane flow rate = 11 litres/minute

		Thermocouple's position (z)(mm)		
		0	69	128
Thermocouple's Number	Thermocouple's Position (x,y)(mm)	Temperature °C	Temperature °C	Temperature °C
00700	(2168,10)	50	51	46
00701	(2168,140)	60	59	55
00701	(2168,270)	54	55	52
00703	(1100,10)	78	88	82
00704	(1100,140)	89	100	109
00705	(1100,270)	76	86	102
00708	(500,10)	193	193	253
00709	(500,140)	88	163	263
00710	(500,270)	45	84	149
00711	(125,10)	480	401	500
00712	(125,140)	120	193	248
00713	(125,270)	43	47	81
00714	(0,140)	67	66	79
00608	(0,270)	39	38	46
00609	(-48,140)	69	70	82
00610	(-48,270)	46	58	51
00611	(-96,140)	56	58	62
00612	(-96,270)	61	58	33

Table A11: Experimental data: Temperature
Trench size: 2438 mm L x 92 mm W x 92 mm H
Trench inclination angle = 30°
Propane flowrate = 2 litres/minute

		Thermocouple Position (z)(mm)	
		0	23
Thermocouple's Number	Thermocouple's Position (x,y)(mm)	Temperature °C	Temperature °C
00700	(2168,5)	28	28
00701	(2168,48)	31	28
00702	(2168,90)	31	28
00703	(1084,5)	57	53
00704	(1084,48)	64	63
00705	(1084,90)	55	57
00708	(542,5)	123	128
00709	(542,48)	144	153
00710	(542,90)	120	128
00711	(271,5)	194	287
00712	(271,48)	246	449
00713	(271,90)	250	299
00714	(136,5)	448	681
00715	(136,48)	18	19
00608	(136,90)	141	154
00609	(68,5)	432	413
00610	(68,48)	164	227
00611	(68,90)	78	81
00612	(0,5)	334	321
00613	(0,48)	96	121
00614	(0,90)	55	57
00615	(-48,5)	369	345
00600	(-48,48)	71	67
00601	(-48,90)	54	53
00602	(-96,5)	81	78
00603	(-96,48)	52	50
00604	(-96,90)	41	40

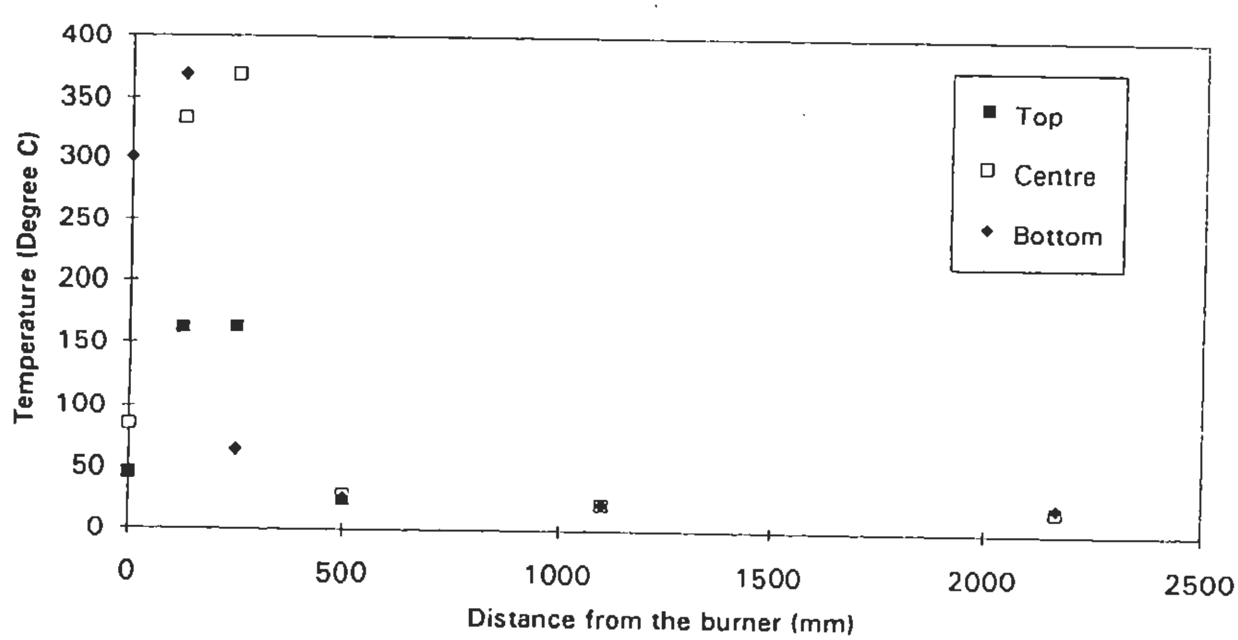
Table A12: Experimental data: Temperature
Trench size: 2438 mm L x 92 mm W x 92 mm H
Trench inclination angle = 30°
Propane flowrate = 6 litres/minute

		Thermocouple Position (z)(mm)	
		0	23
Thermocouple's Number	Thermocouple's Position (x,y)(mm)	Temperature °C	Temperature °C
00700	(2168,5)	38	37
00701	(2168,48)	42	40
00702	(2168,90)	42	37
00703	(1084,5)	107	112
00704	(1084,48)	128	132
00705	(1084,90)	107	108
00708	(542,5)	329	366
00709	(542,48)	400	437
00710	(542,90)	317	341
00711	(271,5)	586	605
00712	(271,48)	537	650
00713	(271,90)	437	468
00714	(136,5)	515	708
00715	(136,48)	18	19
00608	(136,90)	243	359
00609	(68,5)	491	463
00610	(68,48)	373	509
00611	(68,90)	139	238
00612	(0,5)	409	385
00613	(0,48)	180	274
00614	(0,90)	93	101
00615	(-48,5)	412	395
00600	(-48,48)	116	118
00601	(-48,90)	85	89
00602	(-96,5)	135	139
00603	(-96,48)	84	85
00604	(-96,90)	61	65

Table A13: Experimental data: Temperature
Trench size: 2438 mm L x 92 mm W x 92 mm H
Trench inclination angle = 30°
Propane flowrate = 11 litres/minute

Thermocouple's Number	Thermocouple's Position (x,y)(mm)	Thermocouple Position (z)(mm) 0 Temperature °C	23 Temperature °C
00700	(2168,5)	47	43
00701	(2168,48)	53	46
00702	(2168,90)	54	43
00703	(1084,5)	185	164
00704	(1084,48)	249	204
00705	(1084,90)	201	158
00708	(542,5)	605	558
00709	(542,48)	620	591
00710	(542,90)	500	457
00711	(271,5)	756	708
00712	(271,48)	774	800
00713	(271,90)	582	558
00714	(136,5)	537	758
00715	(136,48)	18	19
00608	(136,90)	378	492
00609	(68,5)	507	503
00610	(68,48)	542	729
00611	(68,90)	211	315
00612	(0,5)	467	458
00613	(0,48)	382	446
00614	(0,90)	122	145
00615	(-48,5)	466	457
00600	(-48,48)	171	179
00601	(-48,90)	112	115
00602	(-96,5)	167	184
00603	(-96,48)	111	115
00604	(-96,90)	78	78

Figure A1: Temperature distribution on the symmetrical plane (z=0) of the trench.
Trench inclination angle = 15°
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 6 litres/minute
The "Top" thermocouple was located 270 mm above the trench floor.
The "Centre" thermocouple was located 140 mm above the trench floor.
The "Bottom" thermocouple was located 10 mm above the trench floor.



-ure A2: Temperature distribution on the symmetrical plane (z=0) of the trench.
Trench inclination angle = 17°
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 6 litres/minute
The "Top" thermocouple was located 270 mm above the trench floor.
The "Centre" thermocouple was located 140 mm above the trench floor.
The "Bottom" thermocouple was located 10 mm above the trench floor.

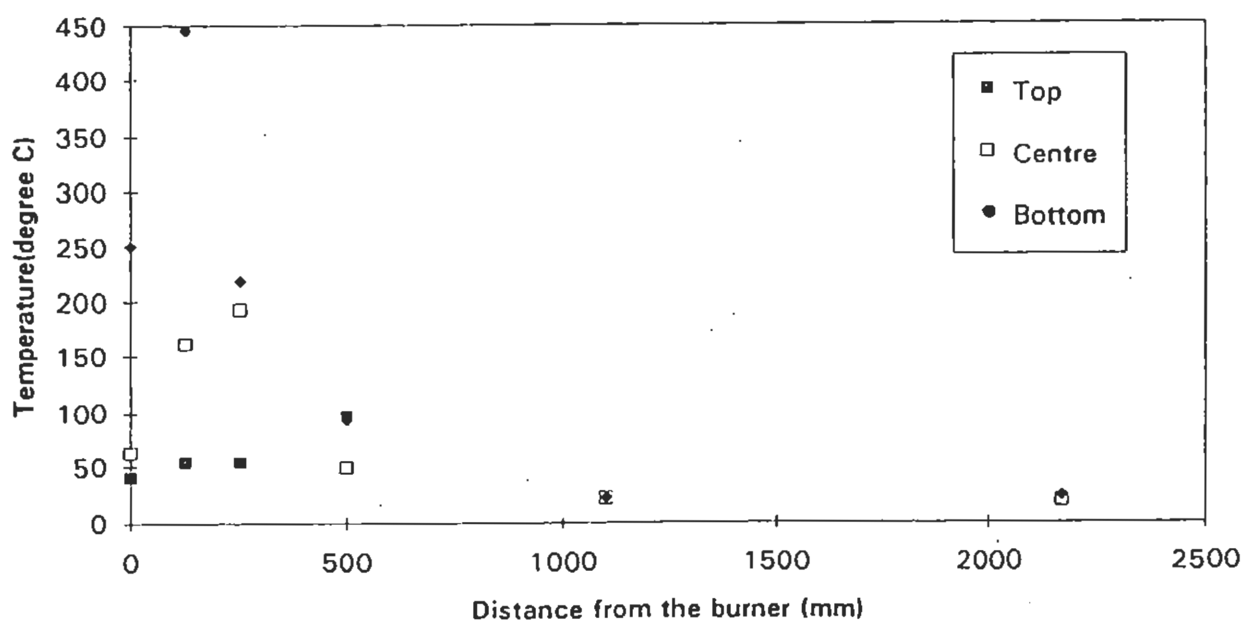
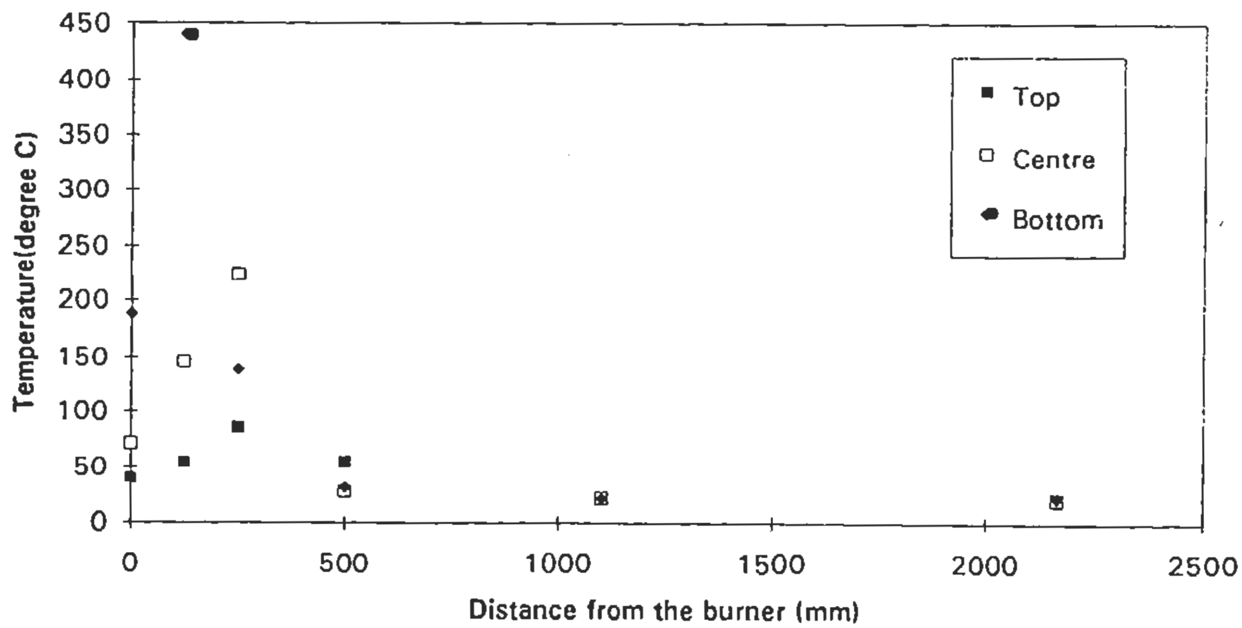


Figure A3: Temperature distribution on the symmetrical plane (z=0) of the trench.
Trench inclination angle = 19°
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 6 litres/minute
The "Top" thermocouple was located 270 mm above the trench floor.
The "Centre" thermocouple was located 140 mm above the trench floor.
The "Bottom" thermocouple was located 10 mm above the trench floor.



;ure A4: Temperature distribution on the symmetrical plane (z=0) of the trench.
Trench inclination angle = 21°
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 6 litres/minute
The "Top" thermocouple was located 270 mm above the trench floor.
The "Centre" thermocouple was located 140 mm above the trench floor.
The "Bottom" thermocouple was located 10 mm above the trench floor.

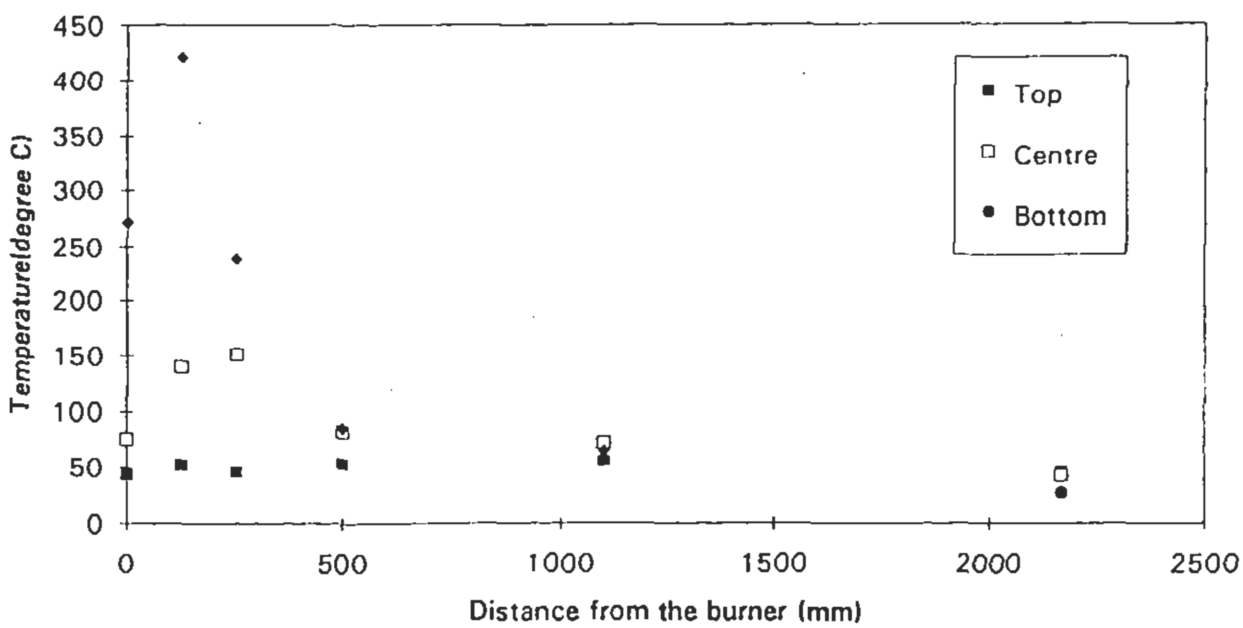
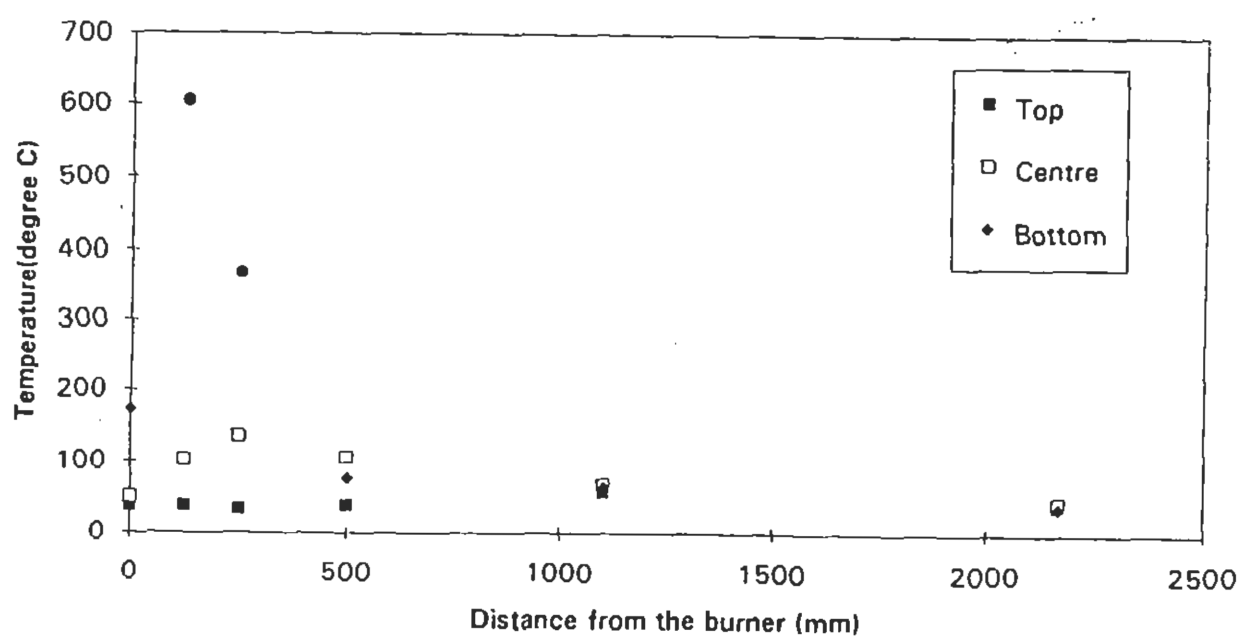


Figure A5: Temperature distribution on the symmetrical plane (z=0) of the trench.
Trench inclination angle = 30°
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 6 litres/minute
The "Top" thermocouple was located 270 mm above the trench floor.
The "Centre" thermocouple was located 140 mm above the trench floor.
The "Bottom" thermocouple was located 10 mm above the trench floor.



ure A6: Temperature distribution on the symmetrical plane (z=0) of the trench.
Trench inclination angle = 17°
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 11 litres/minute
The "Top" thermocouple was located 270 mm above the trench floor.
The "Centre" thermocouple was located 140 mm above the trench floor.
The "Bottom" thermocouple was located 10 mm above the trench floor.

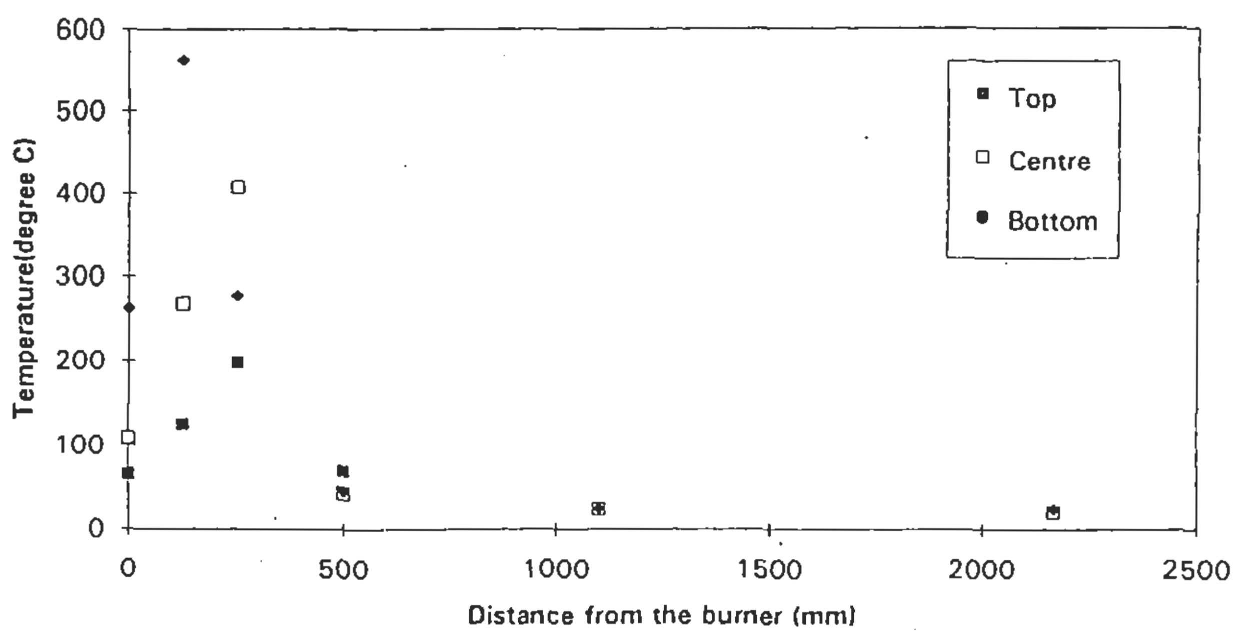
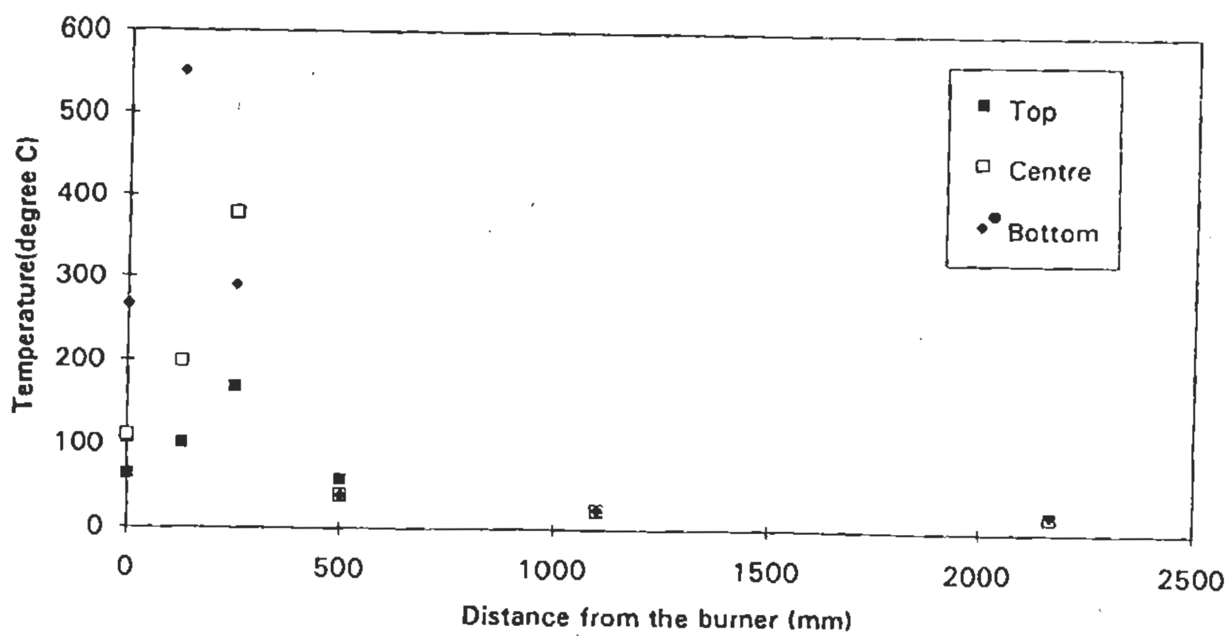


Figure A7: Temperature distribution on the symmetrical plane (z=0) of the trench.
Trench inclination angle = 19°
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 11 litres/minute
The "Top" thermocouple was located 270 mm above the trench floor.
The "Centre" thermocouple was located 140 mm above the trench floor.
The "Bottom" thermocouple was located 10 mm above the trench floor.



ure A8: Temperature distribution on the symmetrical plane (z=0) of the trench.
Trench inclination angle = 21°
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 11 litres/minute
The "Top" thermocouple was located 270 mm above the trench floor.
The "Centre" thermocouple was located 140 mm above the trench floor.
The "Bottom" thermocouple was located 10 mm above the trench floor.

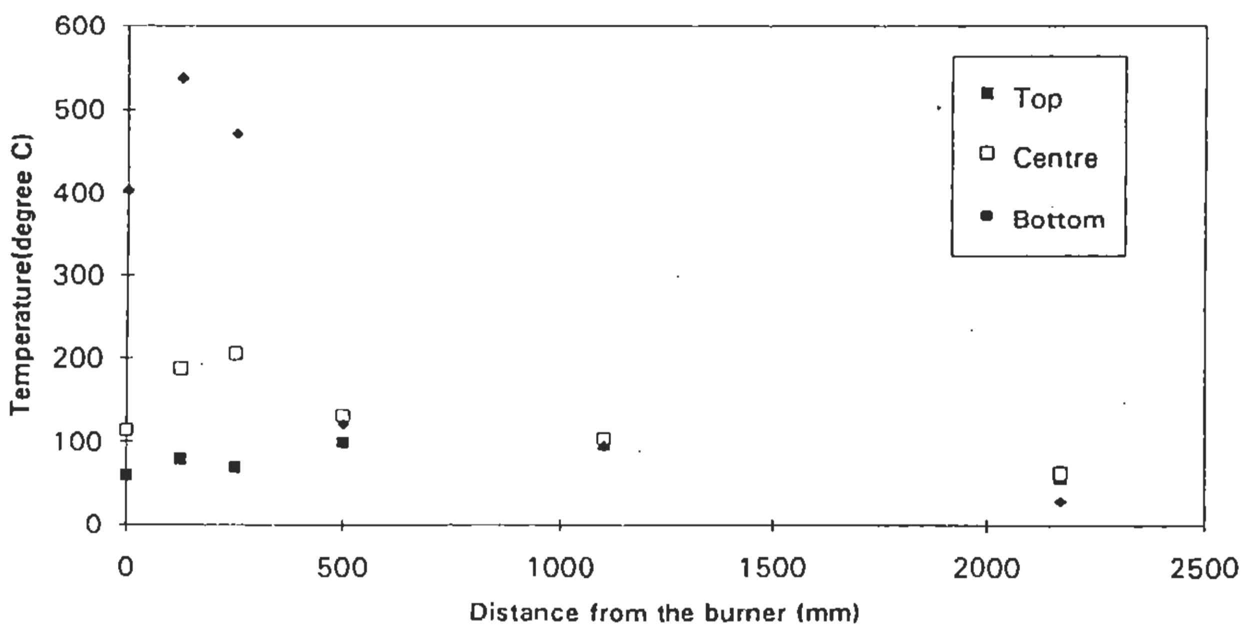
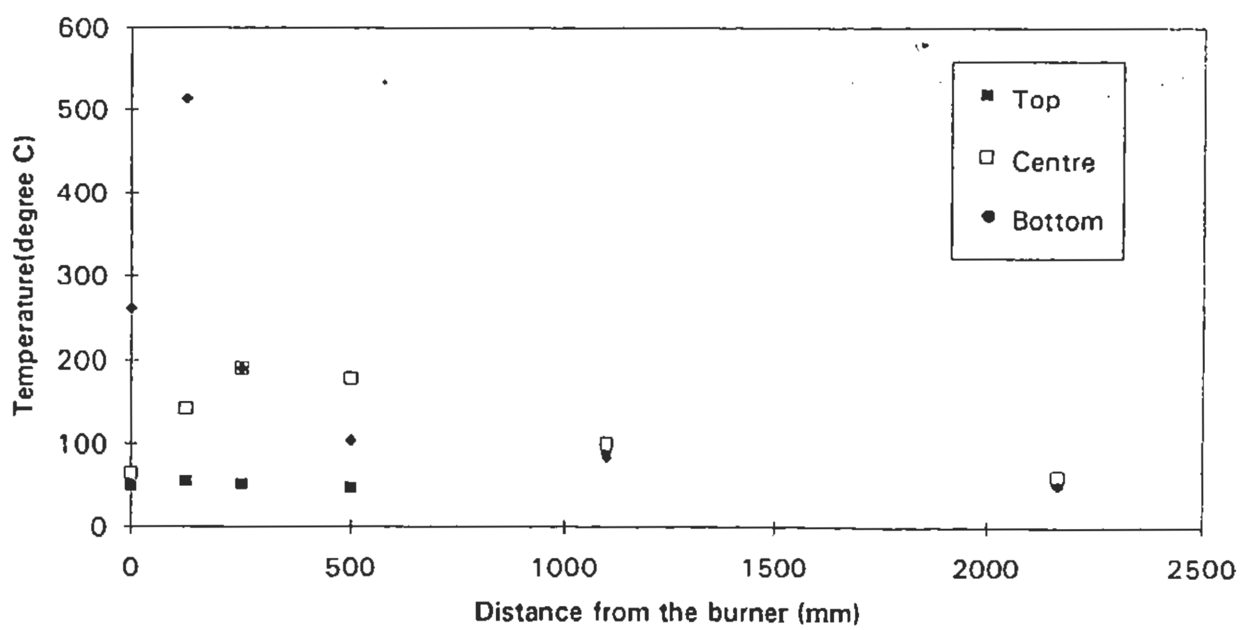


Figure A9: Temperature distribution on the symmetrical plane (z=0) of the trench.
Trench inclination angle = 30°
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 11 litres/minute
The "Top" thermocouple was located 270 mm above the trench floor.
The "Centre" thermocouple was located 140 mm above the trench floor.
The "Bottom" thermocouple was located 10 mm above the trench floor.



gure A10: Temperature distribution on the symmetrical plane (z=0) of the trench.
Trench inclination angle = 15°
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 1 litre/minute
The "Top" thermocouple was located 270 mm above the trench floor.
The "Centre" thermocouple was located 140 mm above the trench floor.
The "Bottom" thermocouple was located 10 mm above the trench floor.

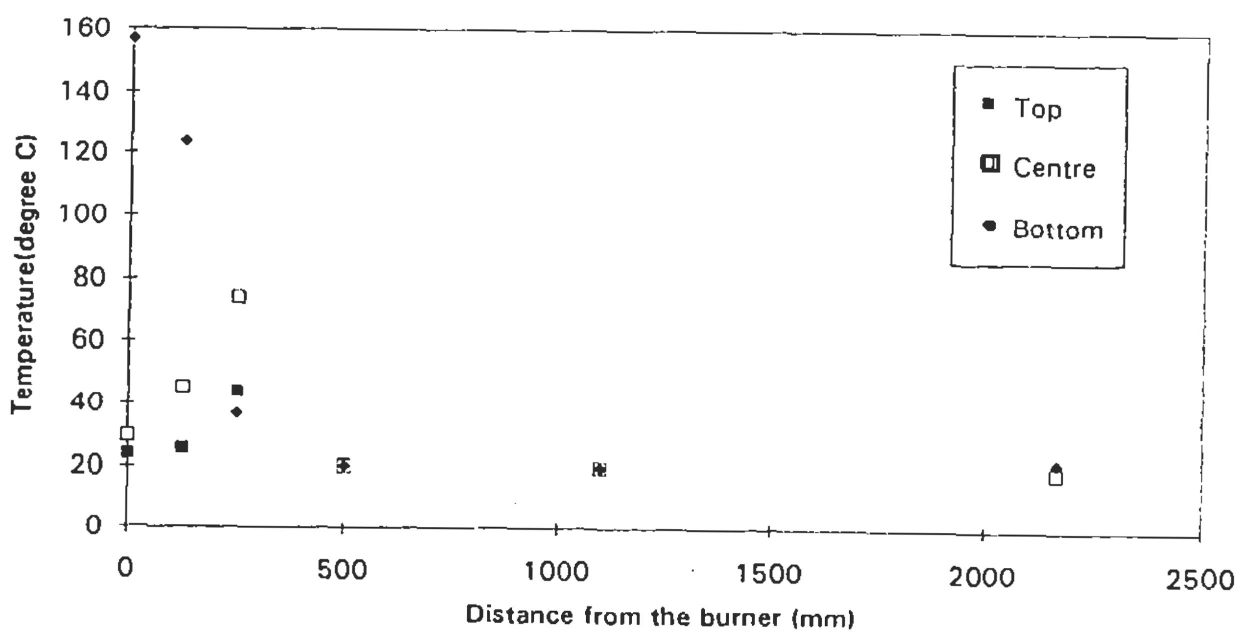


Figure A11: Temperature distribution on the symmetrical plane (z=0) of the trench.
Trench inclination angle = 30°
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 1 litre/minute
The "Top" thermocouple was located 270 mm above the trench floor.
The "Centre" thermocouple was located 140 mm above the trench floor.
The "Bottom" thermocouple was located 10 mm above the trench floor.

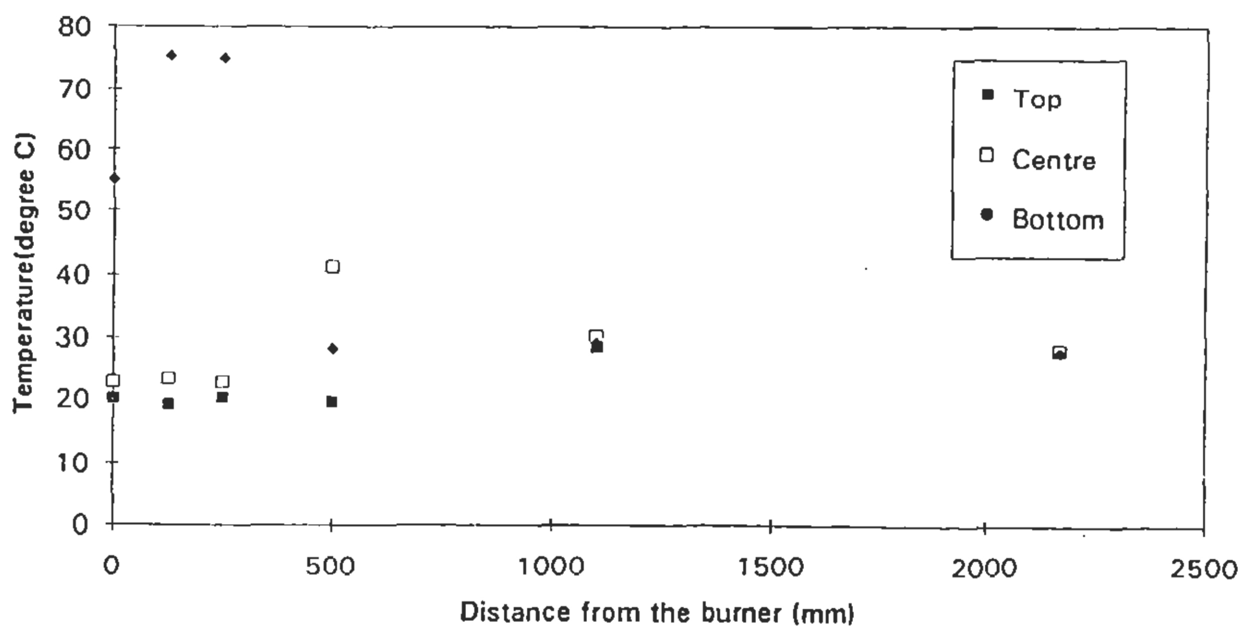


Figure A12: Temperature distribution at the centre of the trench 10 mm above the trench floor (along the centre line y=10 mm and z=0 mm).
Trench inclination angle = 15°
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate was at 1, 6, and 11 litres/minute, respectively.

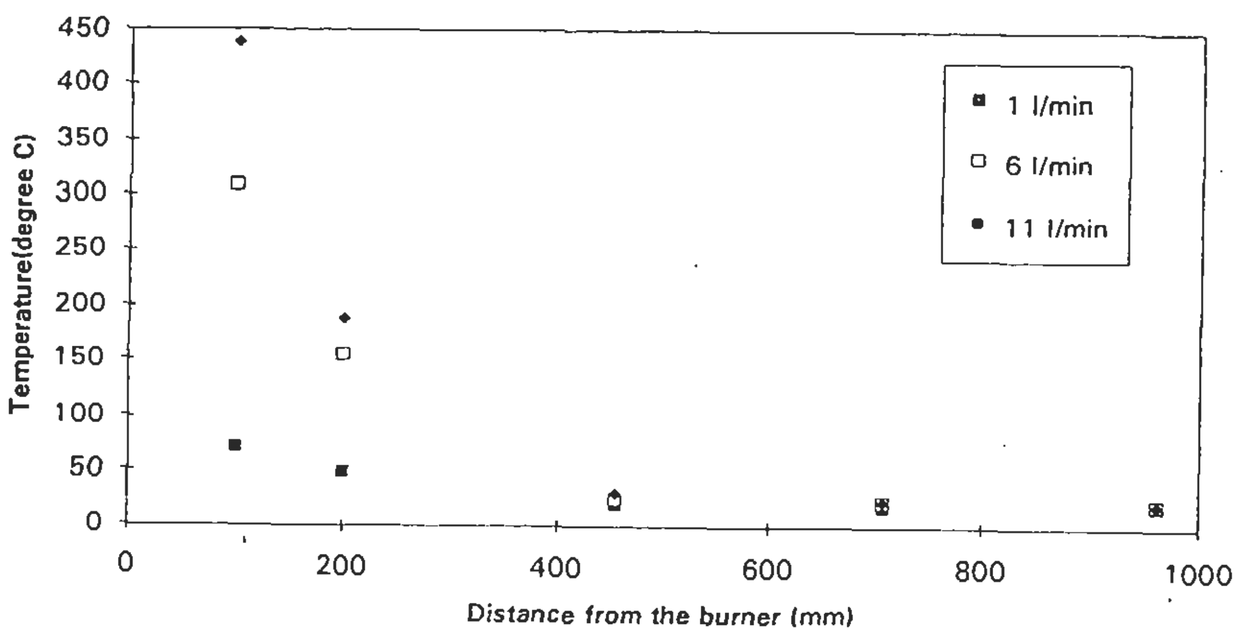


Figure A13: Temperature distribution at the centre of the trench 140 mm above the trench floor (along the centre line y=140 mm and z=0 mm).
Trench inclination angle = 15°
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate was at 1, 6, and 11 litres/minute, respectively.

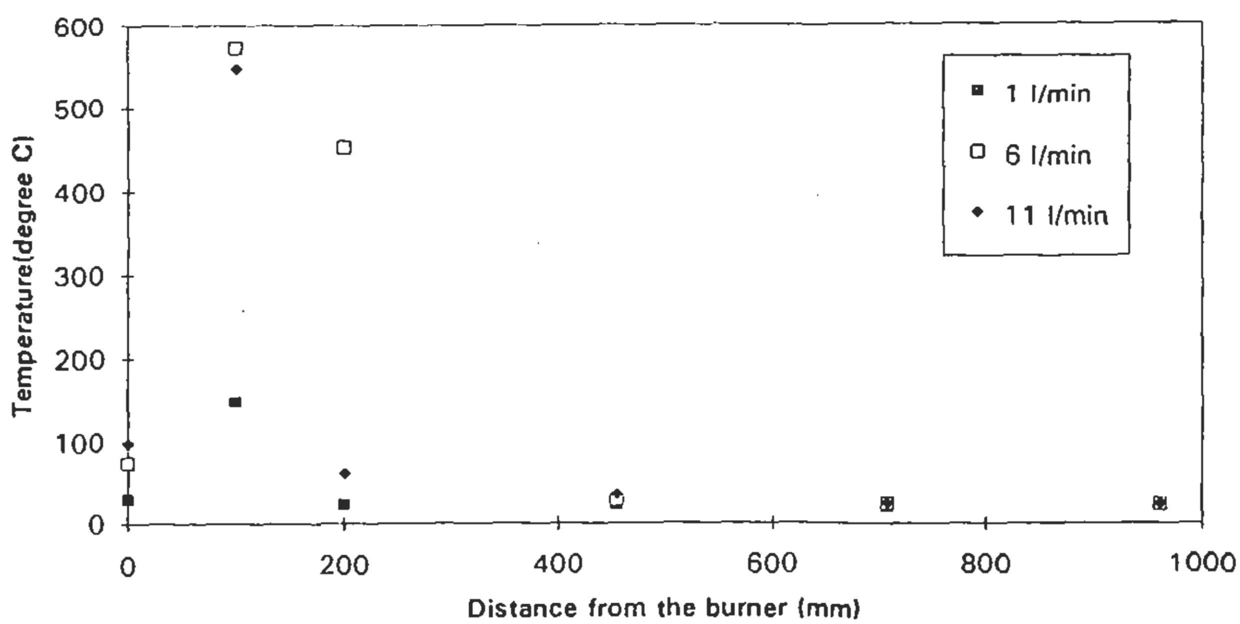


Figure A14: Temperature distribution at the centre of the trench 270 mm above the trench floor (along the centre line y=270 mm and z=0 mm).
Trench inclination angle = 15°
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate was at 1, 6, and 11 litres/minute, respectively.

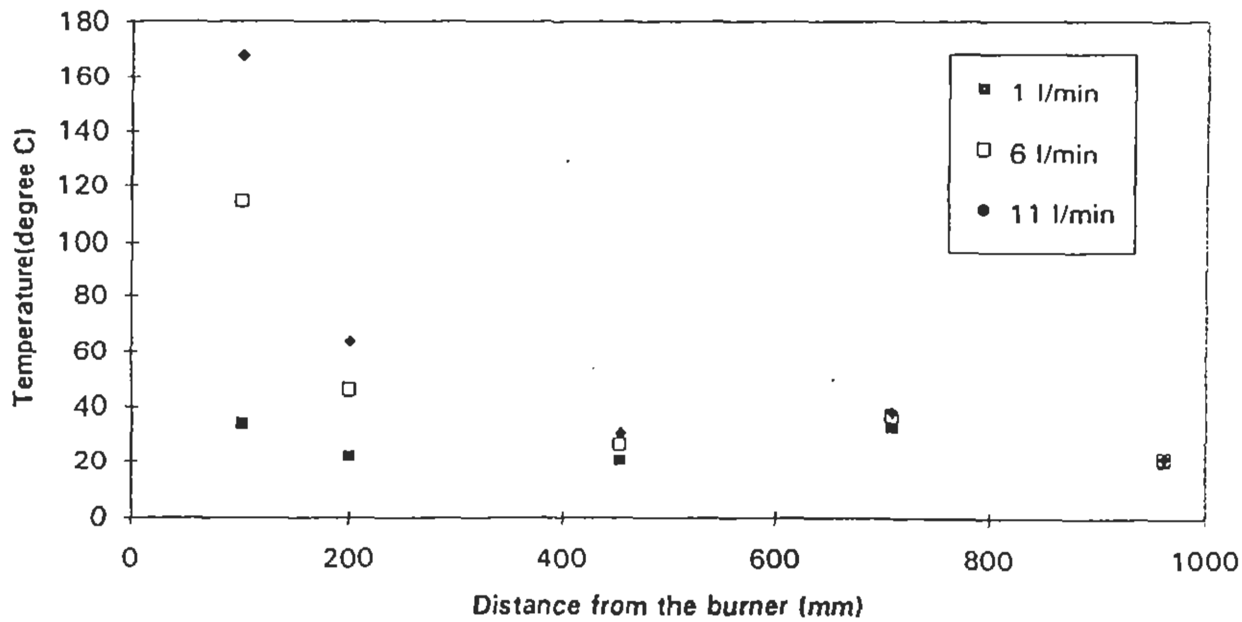


Figure A15: Temperature distribution at the centre of the trench 10 mm above the trench floor (along the centre line y=10 mm and z=0 mm).
Trench inclination angle = 30°
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate was at 1, 6, and 11 litres/minute, respectively.

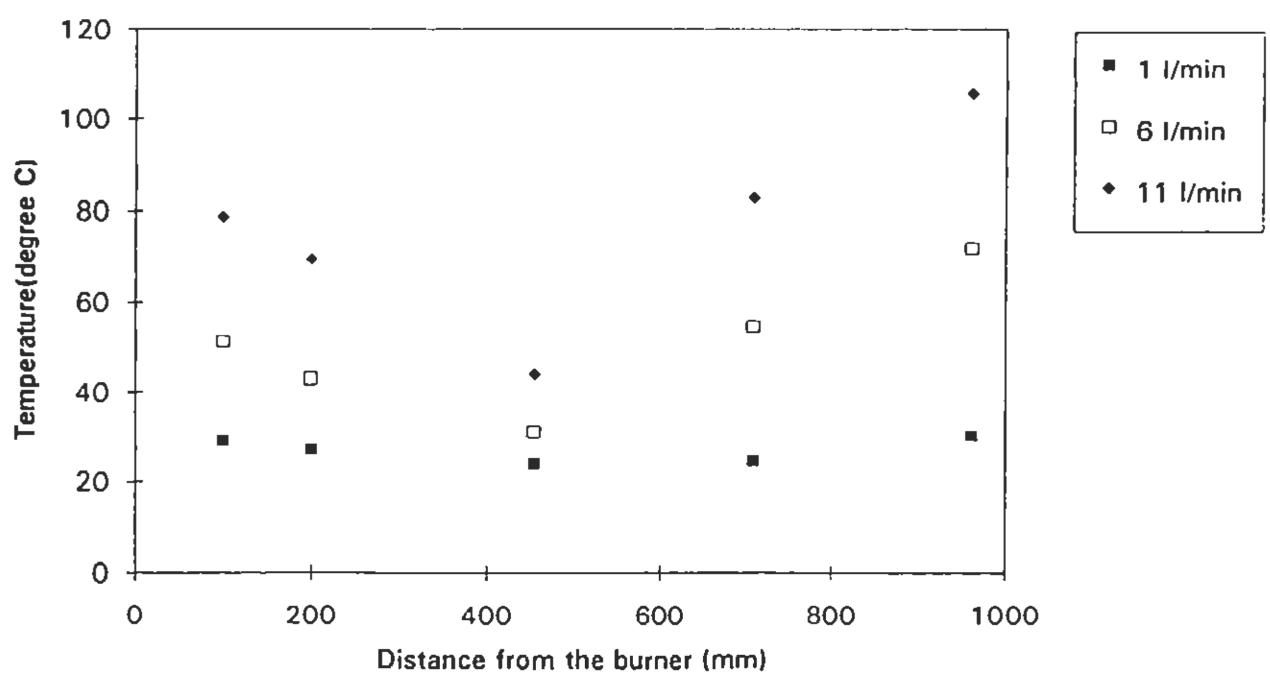


Figure A16: Temperature distribution at the centre of the trench 140 mm above the trench floor (along the centre line y=140 mm and z=0 mm).
Trench inclination angle = 30°
Trench size: 2438 mm L x 276 mm W.x 276 mm H
Propane flow rate was at 1, 6, and 11 litres/minute, respectively.

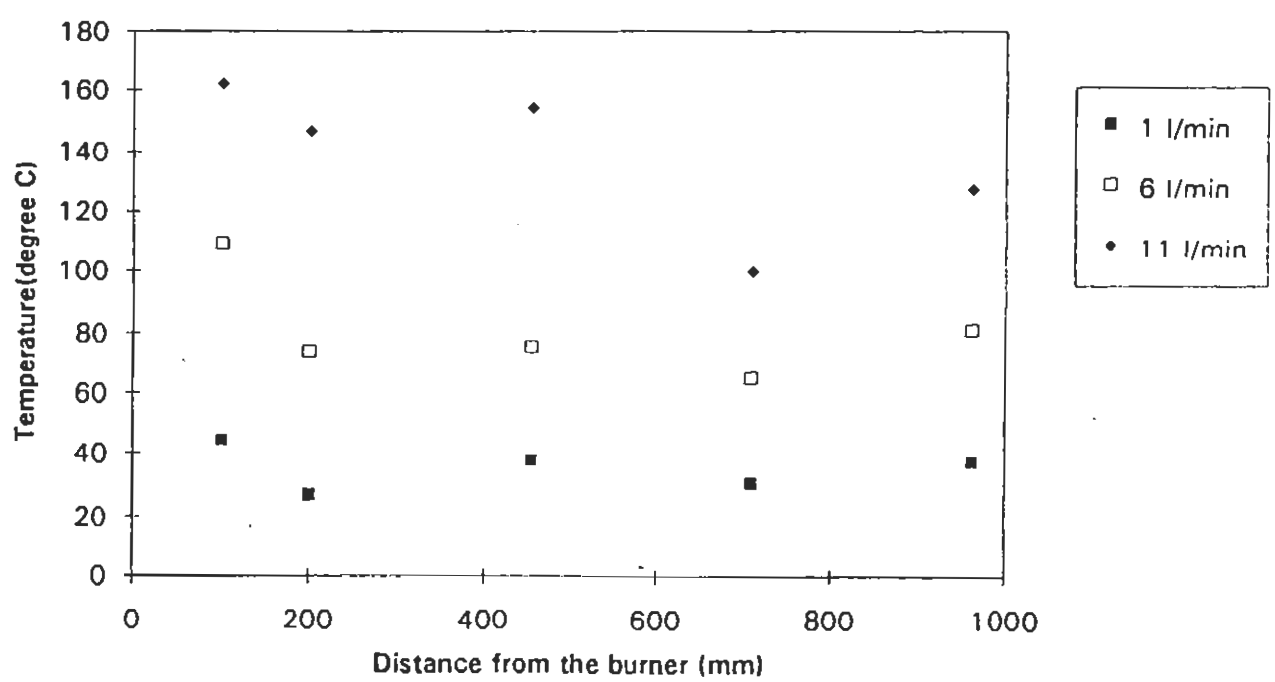


Figure A17: Temperature distribution at the centre of the trench 270 mm above the trench floor (along the centre line y=270 mm and z=0 mm).
Trench inclination angle = 30°
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate was at 1, 6, and 11 litres/minute, respectively.

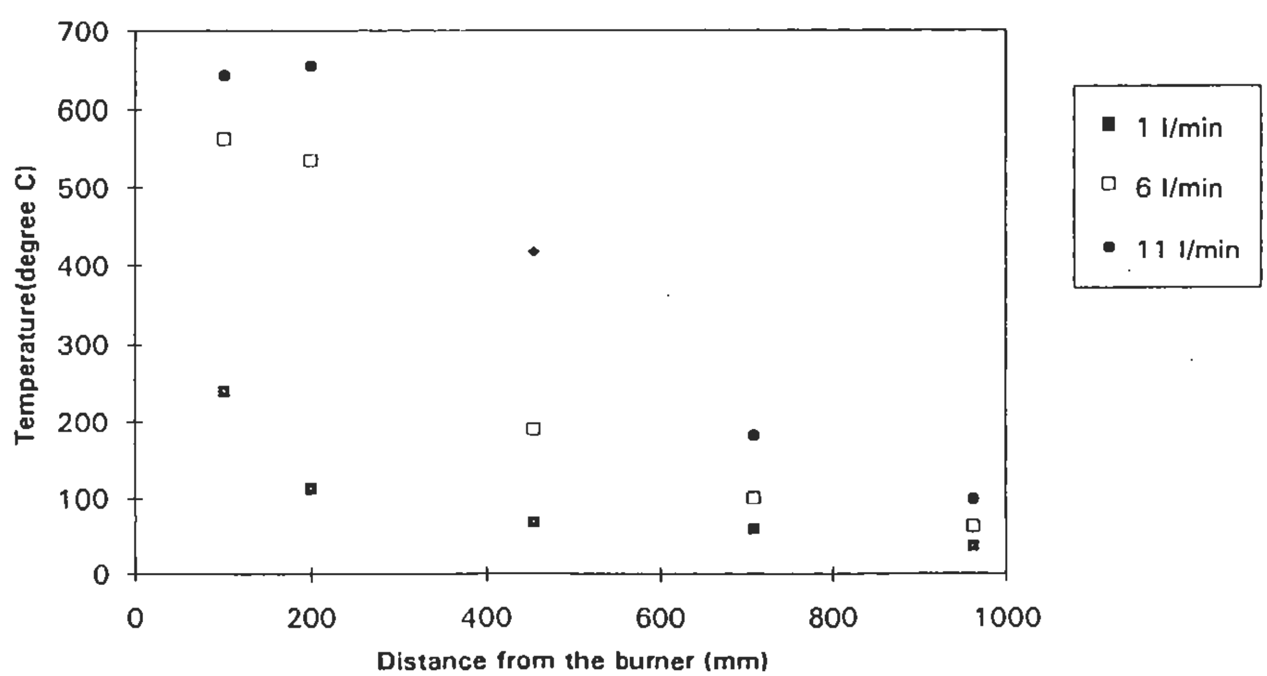


Figure A18: Temperature distribution on the symmetrical plane (z=0 mm) of the trench.
Trench inclination angle = 22°
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 6 litres/minute
The "Top" thermocouple is located 270 mm above the trench floor.
The "Centre" thermocouple is located 140 mm above the trench floor.
The "Bottom" thermocouple is located 10 mm above the trench floor.

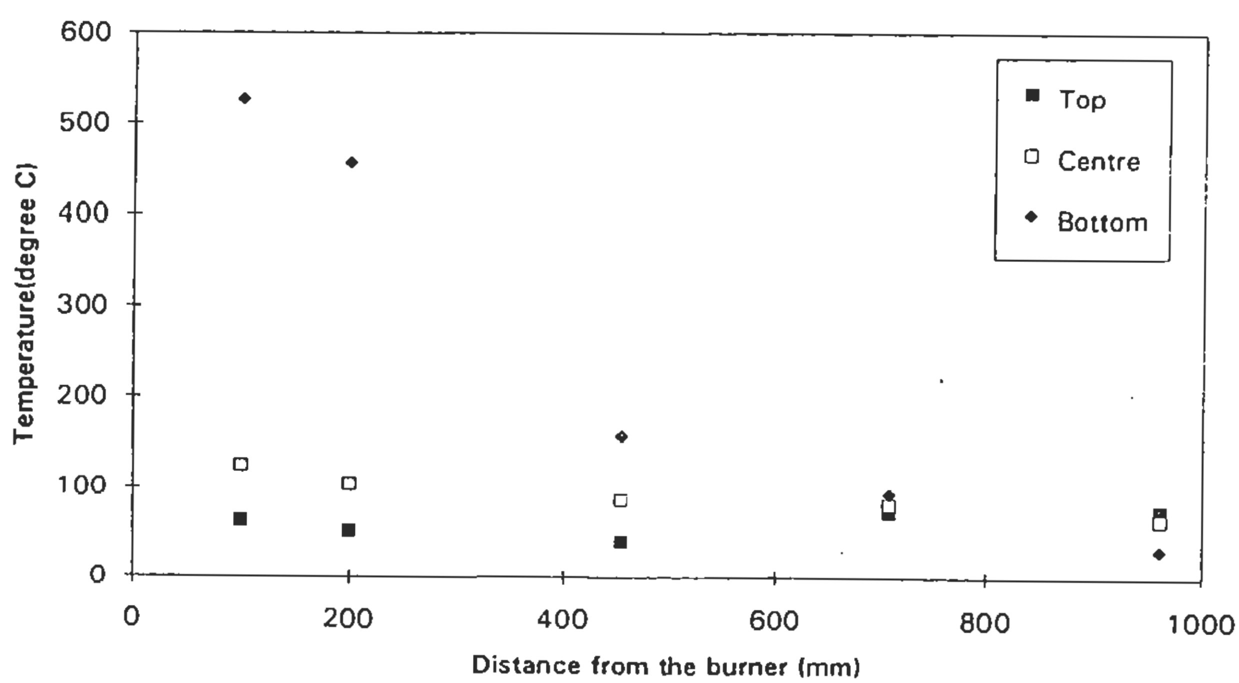


Figure A19: Temperature distribution on the symmetrical plane (z=0 mm) of the trench.
Trench inclination angle = 24°
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 6 litres/minute
The "Top" thermocouple is located 270 mm above the trench floor.
The "Centre" thermocouple is located 140 mm above the trench floor.
The "Bottom" thermocouple is located 10 mm above the trench floor.

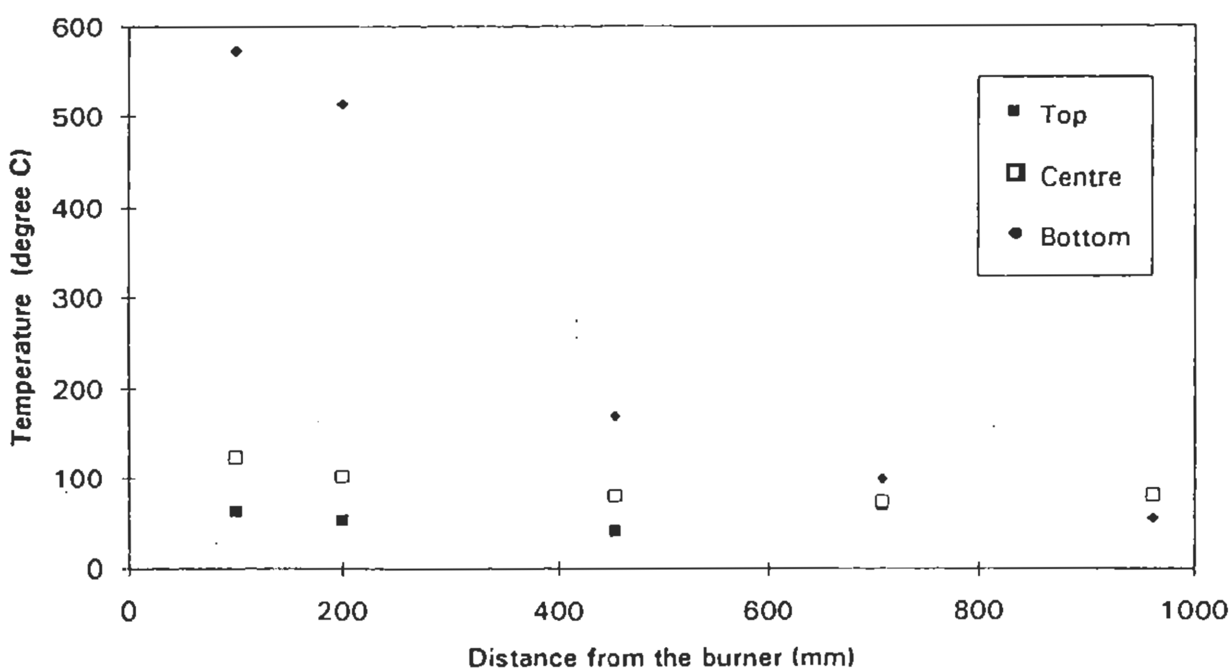


Figure A20: Temperature distribution on the symmetrical plane (z=0 mm) of the trench.
Trench inclination angle = 26°
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 6 litres/minute
The "Top" thermocouple is located 270 mm above the trench floor.
The "Centre" thermocouple is located 140 mm above the trench floor.
The "Bottom" thermocouple is located 10 mm above the trench floor.

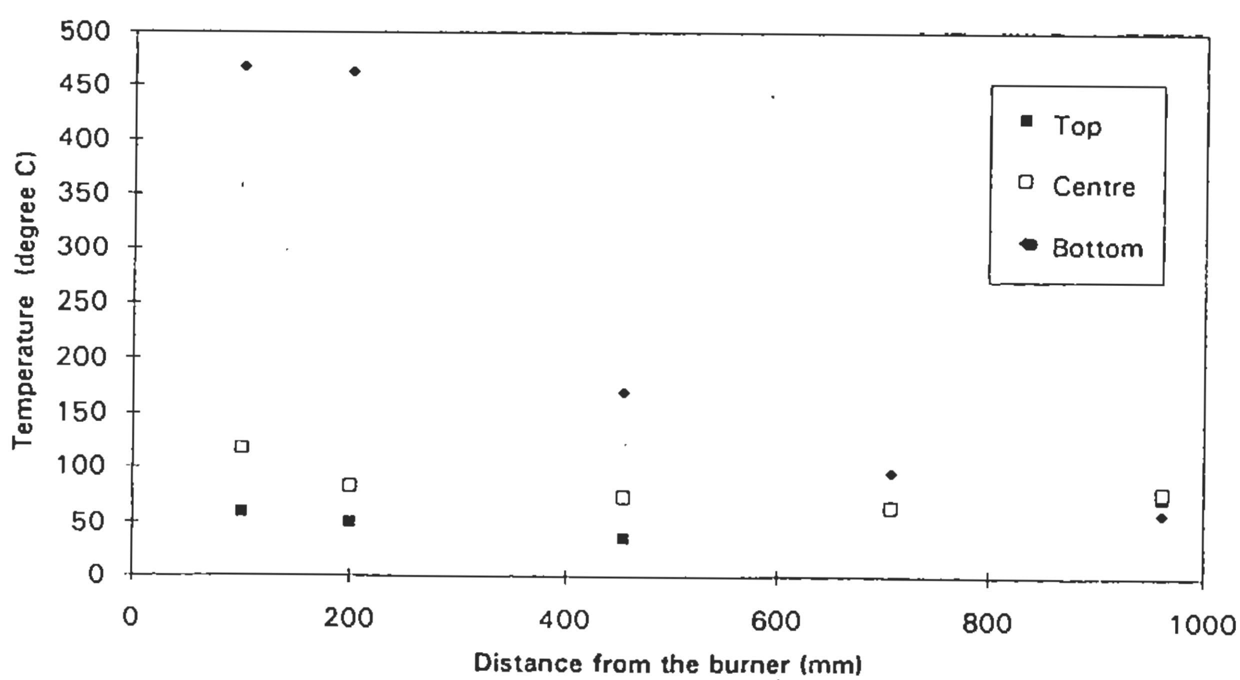


Figure A21: Temperature distribution inside the trench on the symmetrical plane z=0 mm.
Trench inclination angle = 30°
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 1 litre/minute
The "Top" thermocouple is located 270 mm above the trench floor.
The "Centre" thermocouple is located 140 mm above the trench floor.
The "Bottom" thermocouple is located 10 mm above the trench floor.

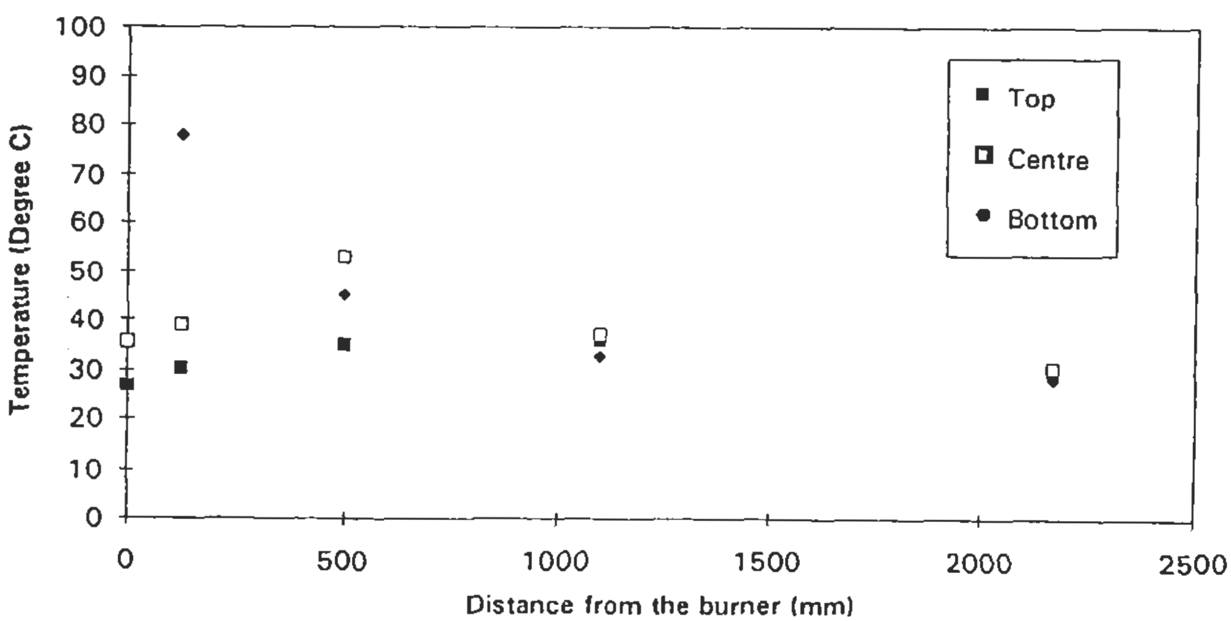


Figure A22: Temperature distribution inside the trench on the plane of z = 69 mm.
Trench inclination angle = 30 °
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 1 litre/minute
The "Top" thermocouple is located 270 mm above the trench floor.
The "Centre" thermocouple is located 140 mm above the trench floor.
The "Bottom" thermocouple is located 10 mm above the trench floor.

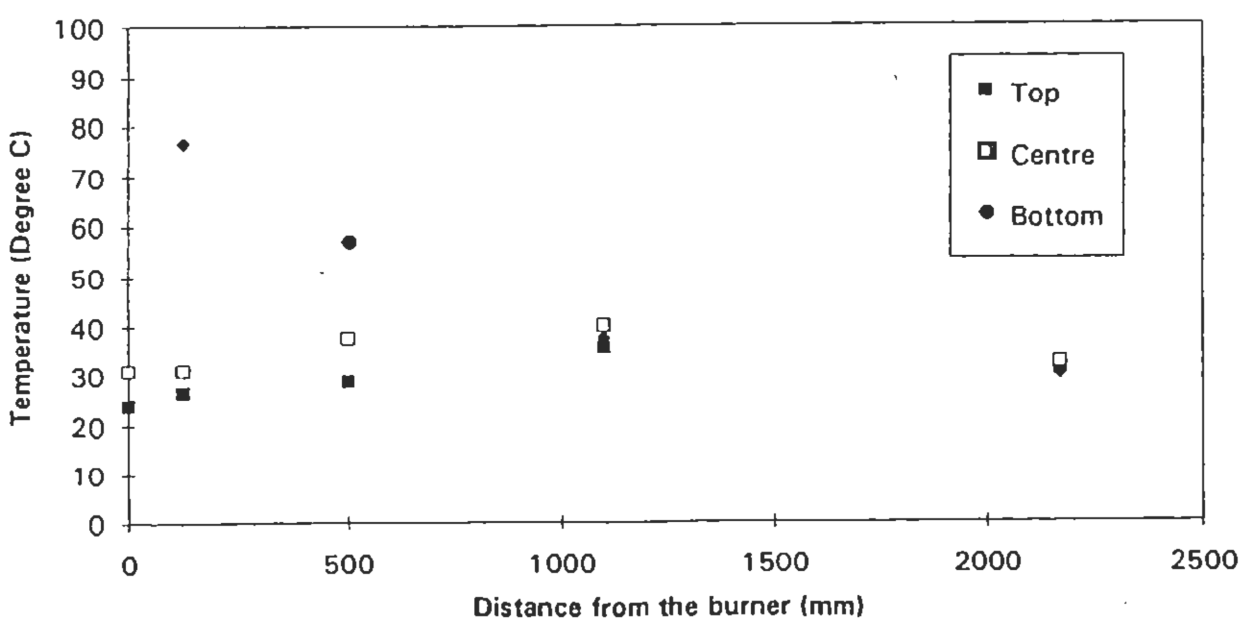


Figure A23: Temperature distribution inside the trench on the plane of z = 128 mm.
Trench inclination angle = 30°
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 1 litre/minute
The "Top" thermocouple is located 270 mm above the trench floor.
The "Centre" thermocouple is located 140 mm above the trench floor.
The "Bottom" thermocouple is located 10 mm above the trench floor.

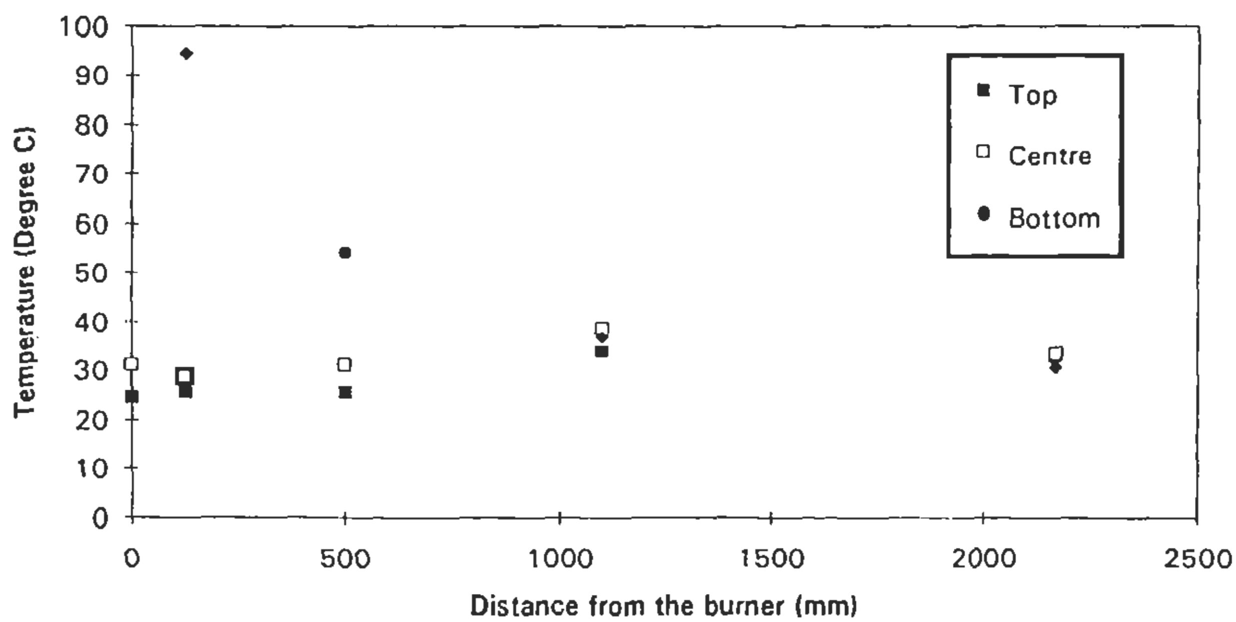


Figure A24: Temperature distribution cross the trench cross-section of plane at x = 125 mm and y = 270 mm.
Trench inclination angle = 30 °
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 1 litre/minute

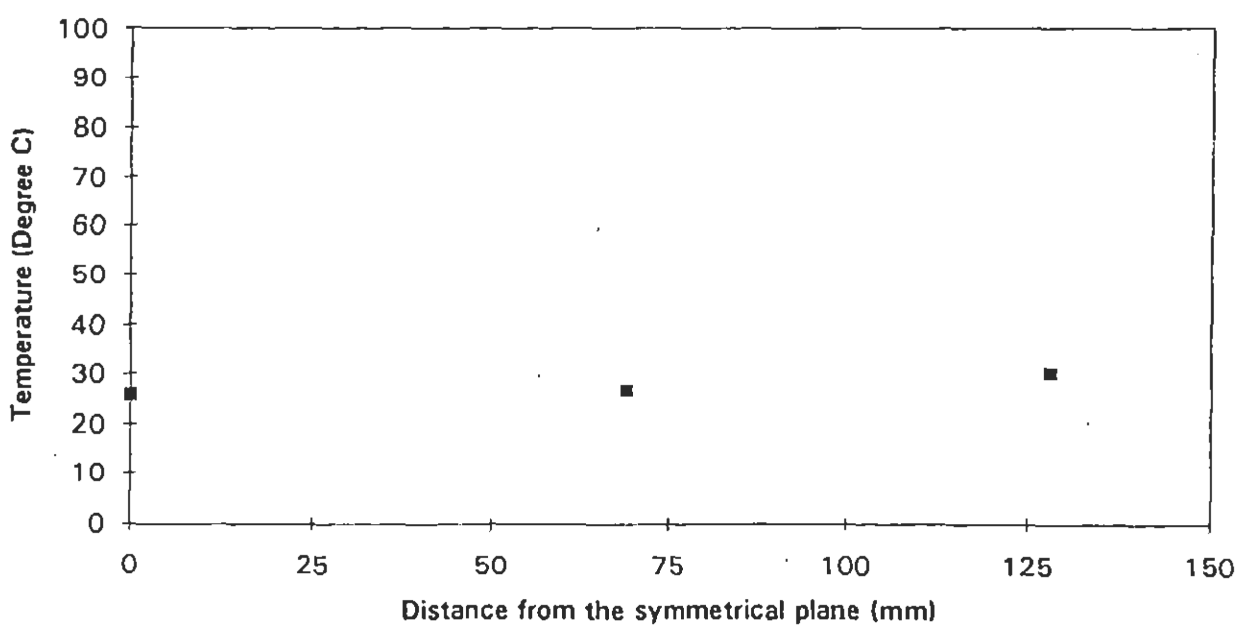


Figure A25: Temperature distribution cross the trench cross-section of plane at x = 125 mm and y = 140 mm.
Trench inclination angle = 30°
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 1 litre/minute

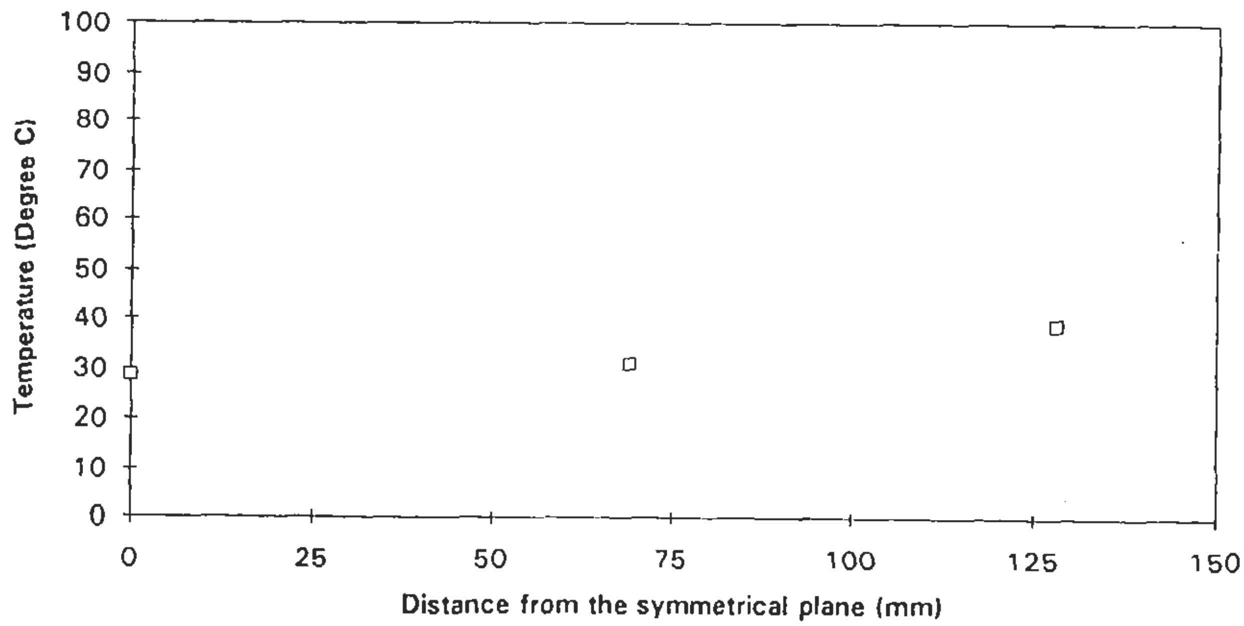


Figure A26: Temperature distribution cross the trench cross-section of plane at x = 125 mm and y = 10 mm.
Trench inclination angle = 30 °
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 1 litre/minute

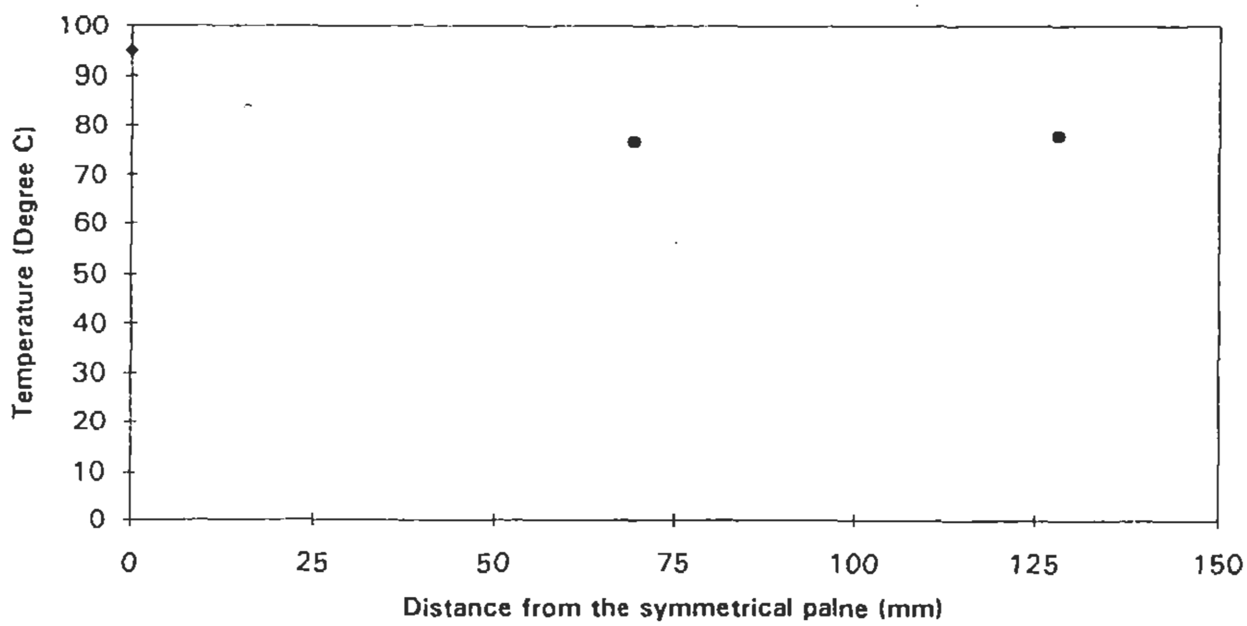


Figure A27: Temperature distribution cross the trench cross-section of plane at x = 500 mm and y = 270 mm.
Trench inclination angle = 30 °
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 1 litre/minute

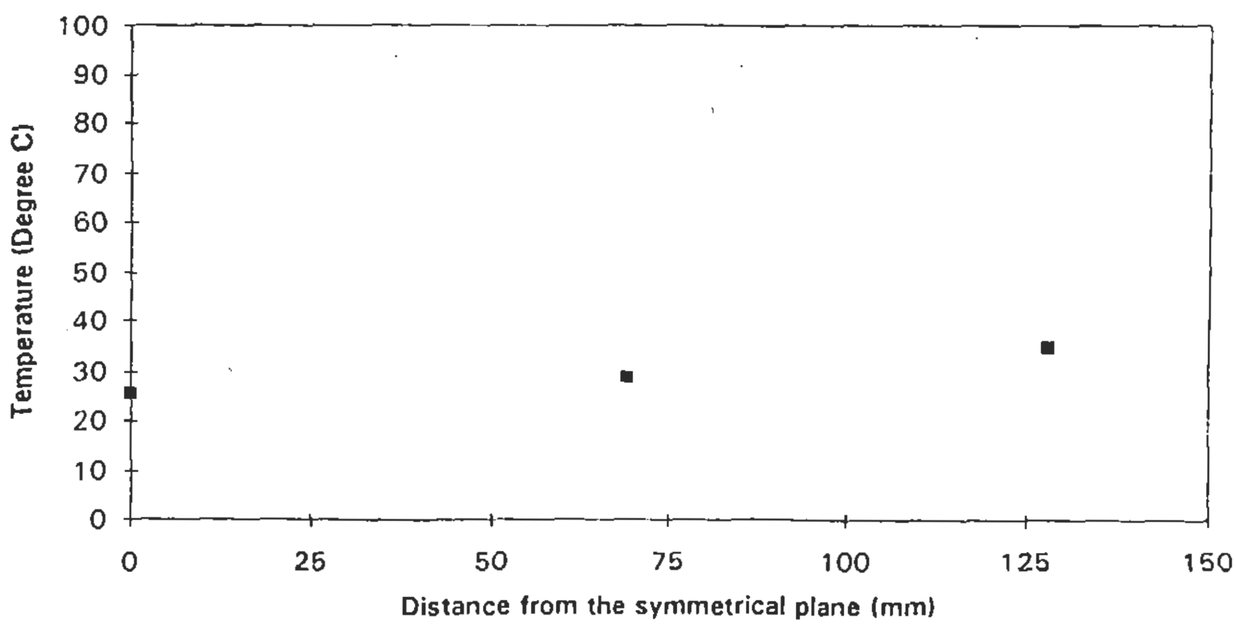


Figure A28: Temperature distribution cross the trench cross-section of plane at x = 500 mm and y = 140 mm.
Trench inclination angle = 30 °
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 1 litre/minute

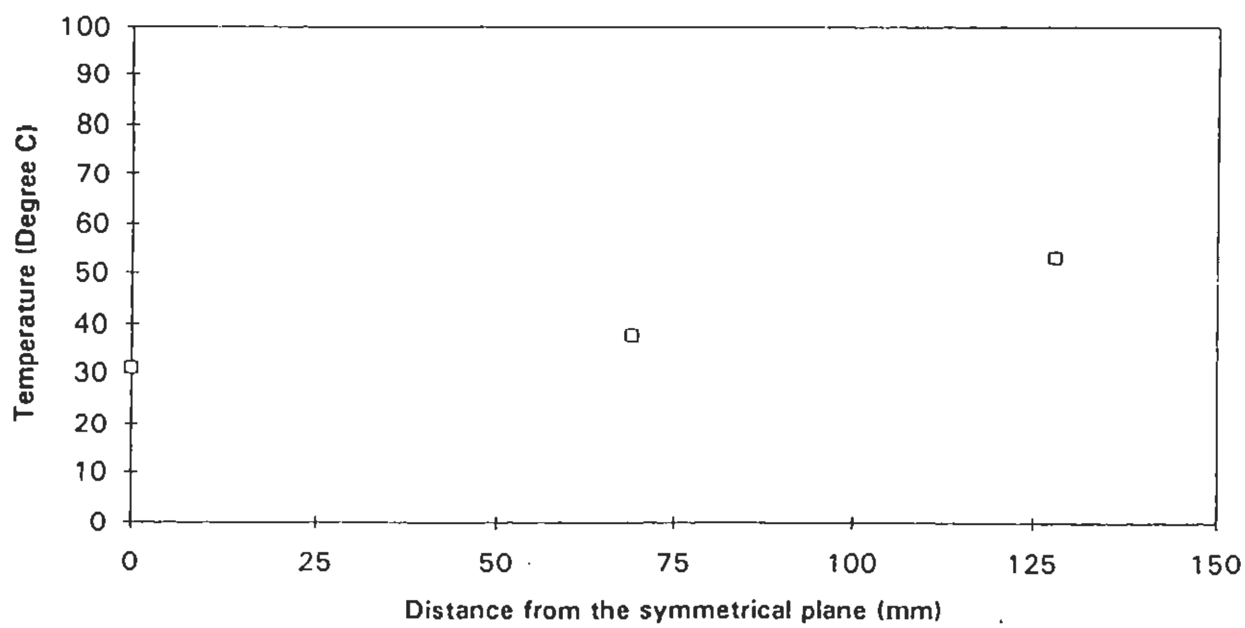
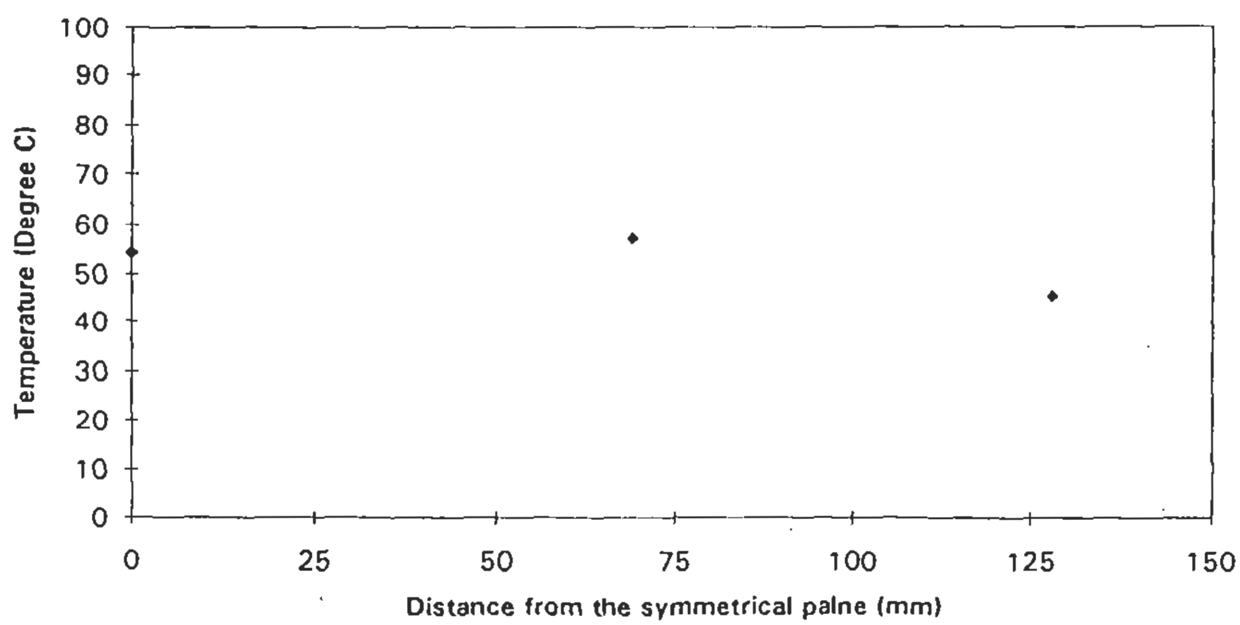


Figure A29: Temperature distribution cross the trench cross-section of plane at x = 500 mm and y = 10 mm.
Trench inclination angle = 30 °
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 1 litre/minute



igure A30: Temperature distribution inside the trench on the symmetrical plane z=0 mm.
Trench inclination angle = 30°
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 6 litres/minute
The "Top" thermocouple is located 270 mm above the trench floor.
The "Centre" thermocouple is located 140 mm above the trench floor.
The "Bottom" thermocouple is located 10 mm above the trench floor.

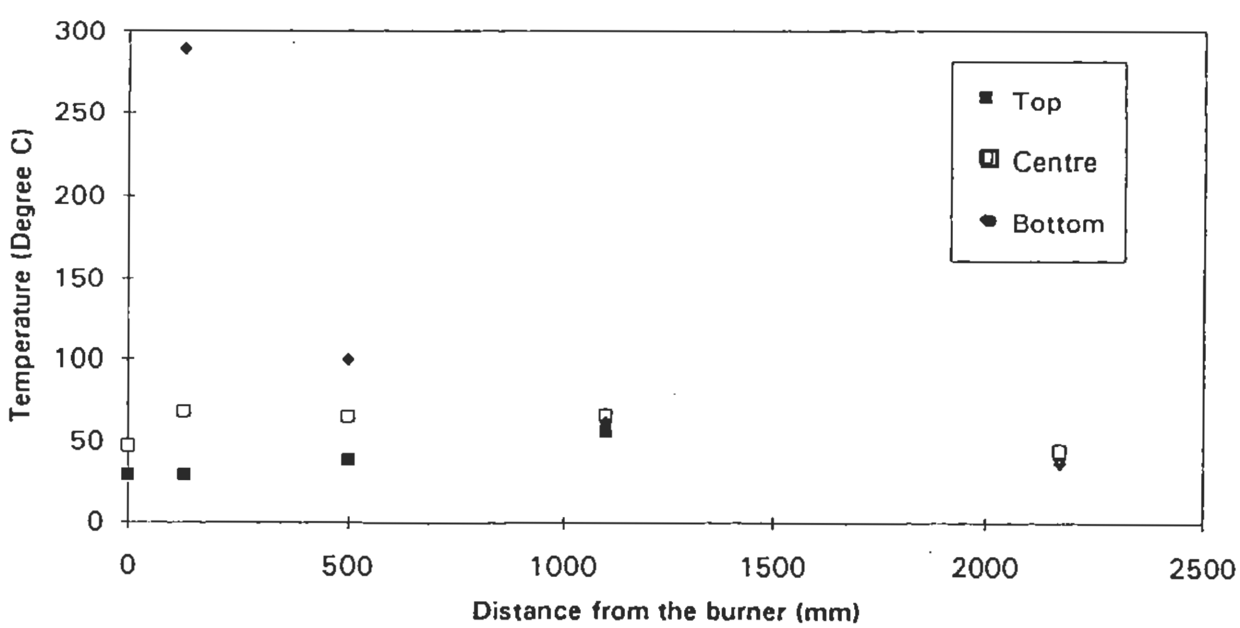


Figure A31: Temperature distribution inside the trench on the plane of z = 69 mm.
Trench inclination angle = 30 °
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 6 litres/minute
The "Top" thermocouple is located 270 mm above the trench floor.
The "Centre" thermocouple is located 140 mm above the trench floor.
The "Bottom" thermocouple is located 10 mm above the trench floor.

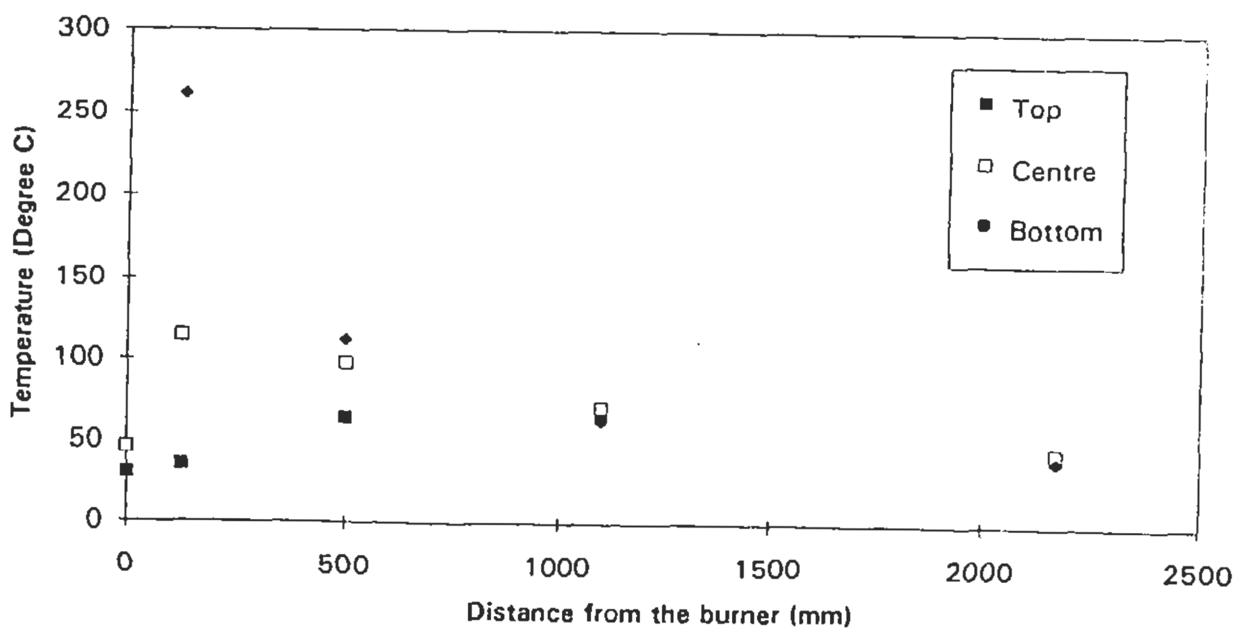


Figure A32: Temperature distribution inside the trench on the plane of z = 128 mm.
Trench inclination angle = 30°
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 6 litres/minute
The "Top" thermocouple is located 270 mm above the trench floor.
The "Centre" thermocouple is located 140 mm above the trench floor.
The "Bottom" thermocouple is located 10 mm above the trench floor.

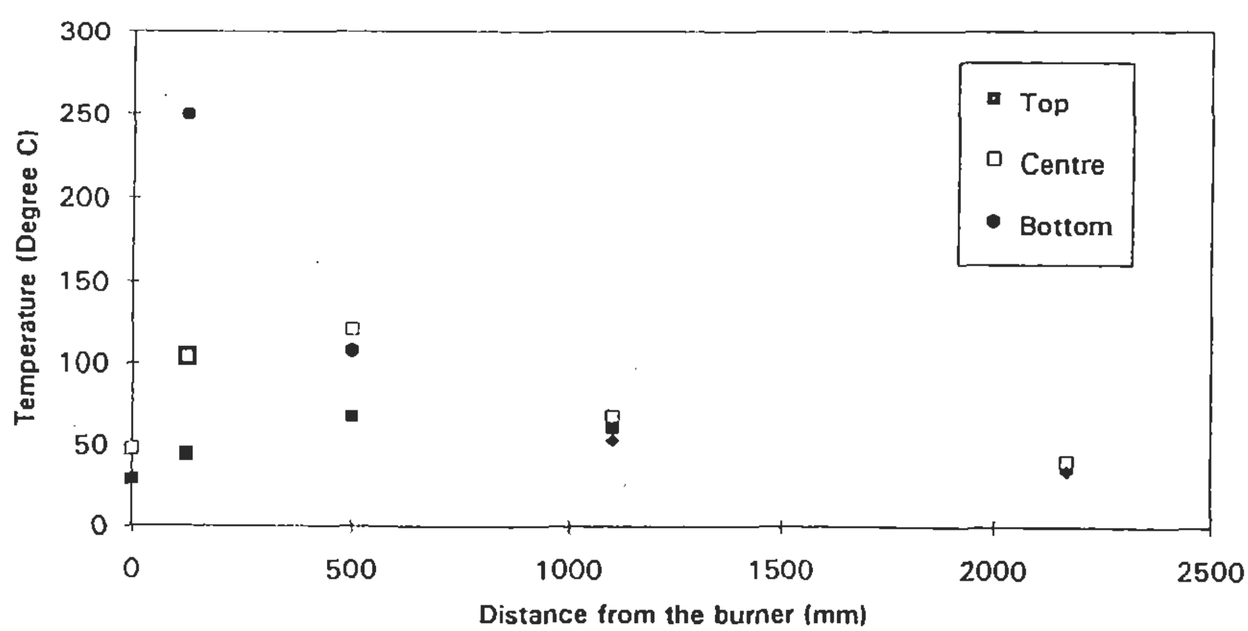


Figure A33: Temperature distribution cross the trench cross-section of plane at x = 125 mm and y = 270 mm.
Trench inclination angle = 30 °
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 6 litres/minute

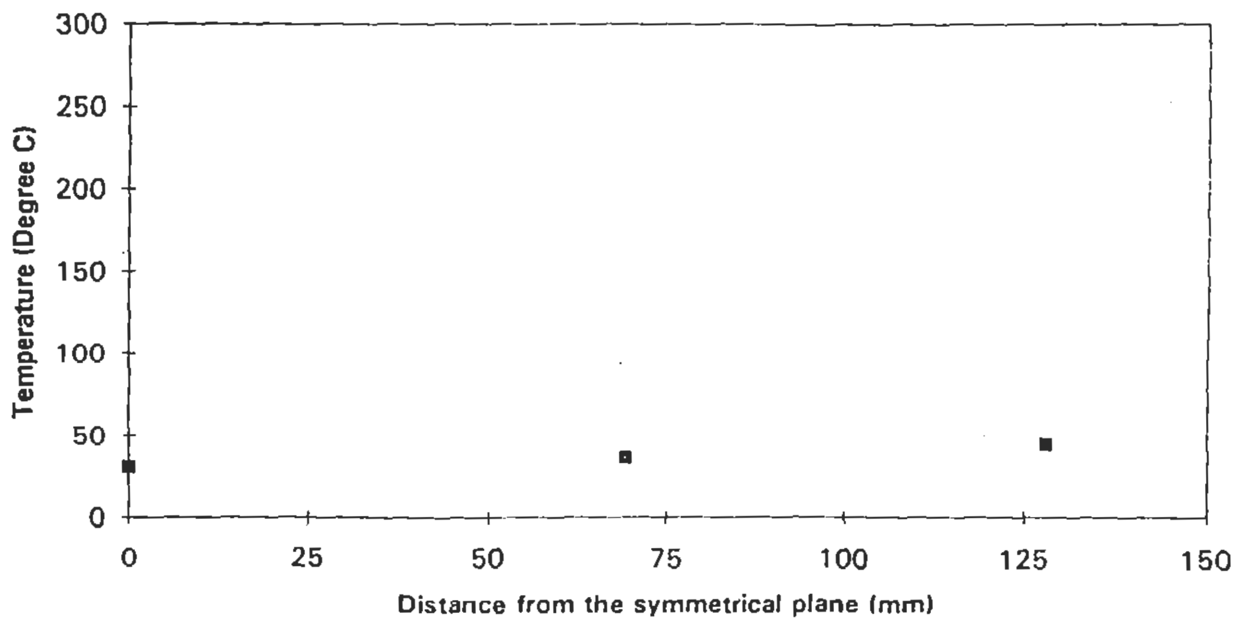


Figure A34: Temperature distribution cross the trench cross-section of plane at x = 125 mm and y = 140 mm.
Trench inclination angle = 30°
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 6 litres/minute

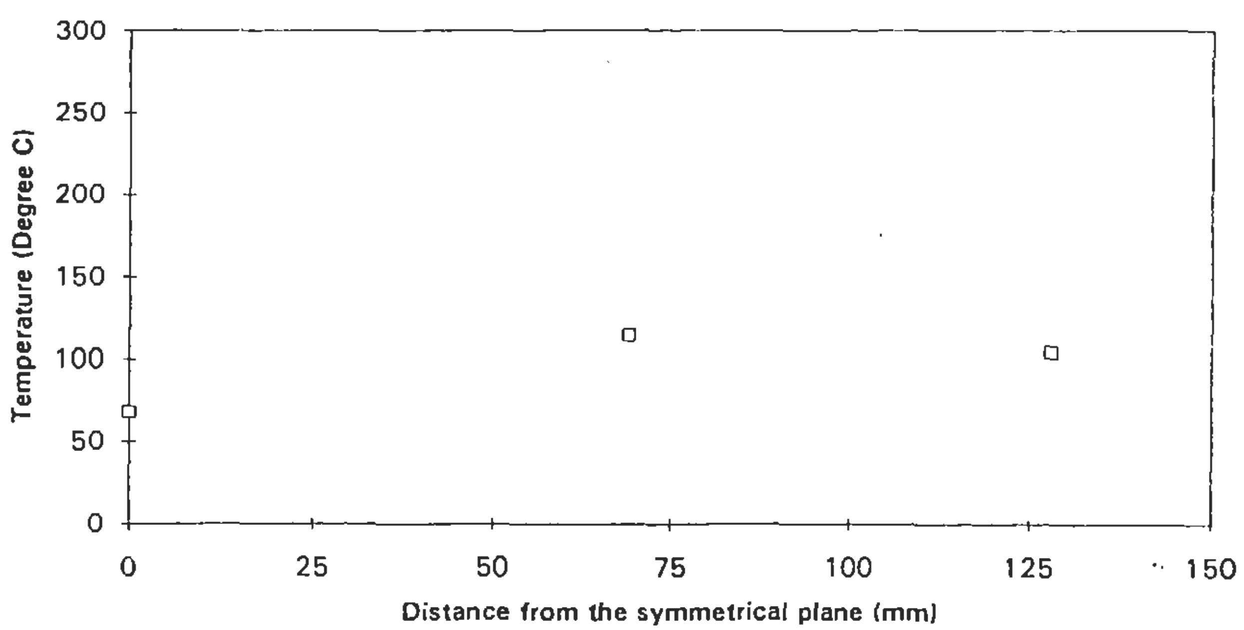


Figure A35: Temperature distribution cross the trench cross-section of plane at x = 125 mm and y = 10 mm.
Trench inclination angle = 30 °
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 6 litres/minute

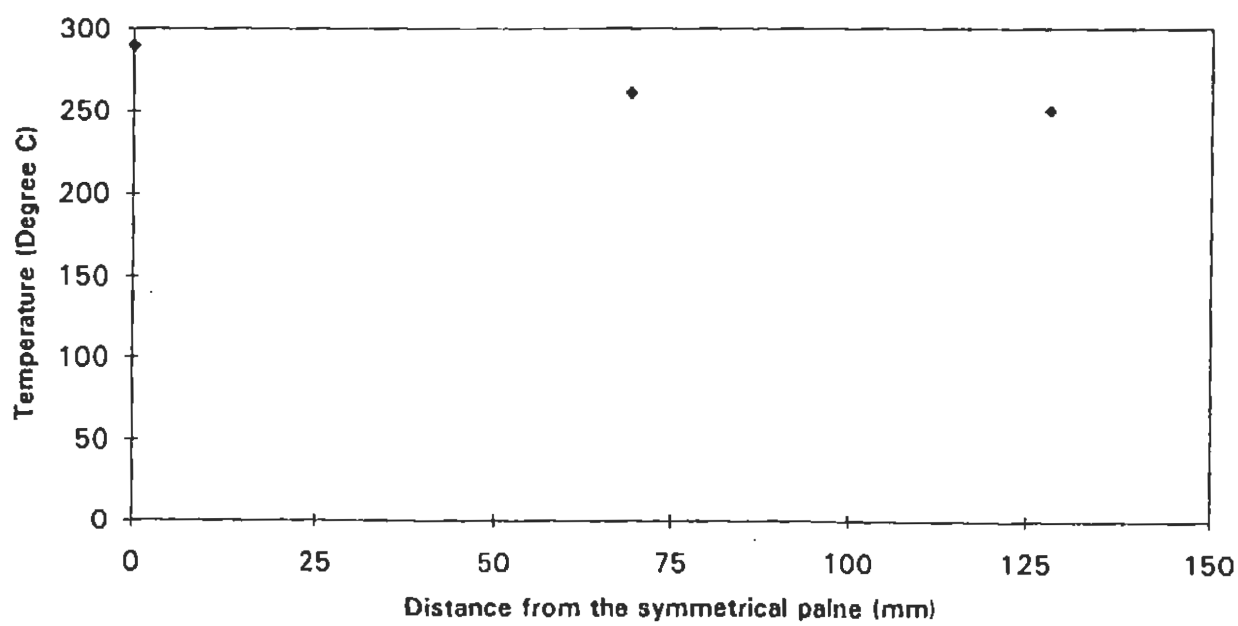


Figure A36: Temperature distribution cross the trench cross-section of plane at x = 500 mm and y = 270 mm.
Trench inclination angle = 30°
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 6 litres/minute

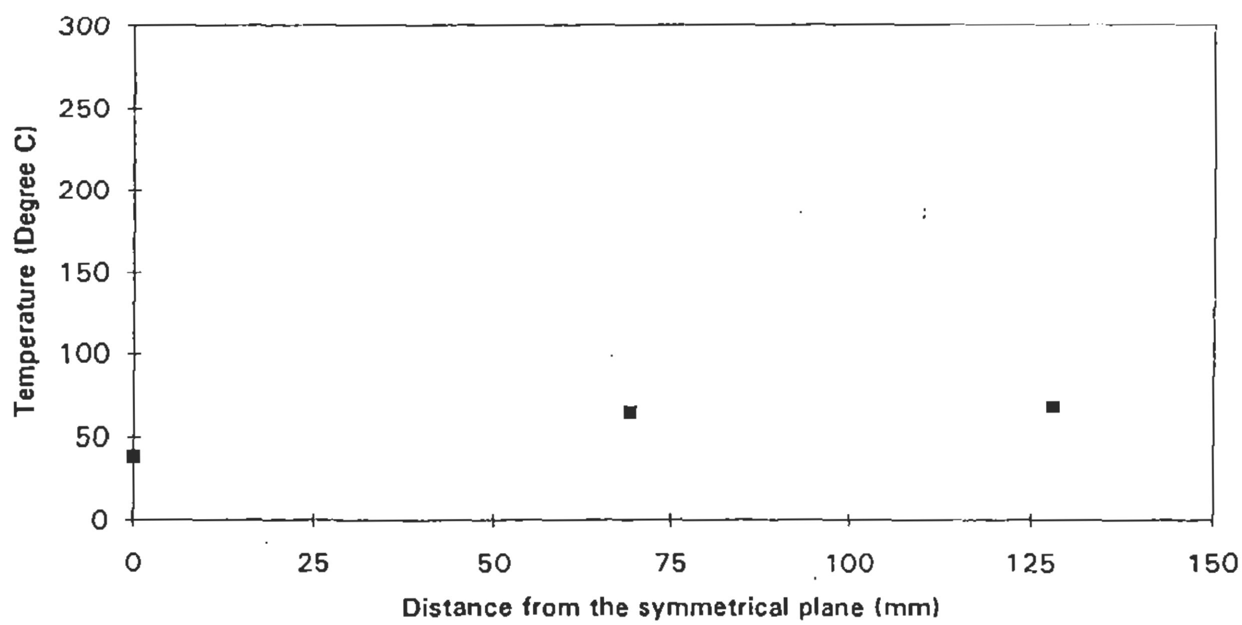


Figure A37: Temperature distribution cross the trench cross-section of plane at x = 500 mm and y = 140 mm.
Trench inclination angle = 30°
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 6 litres/minute

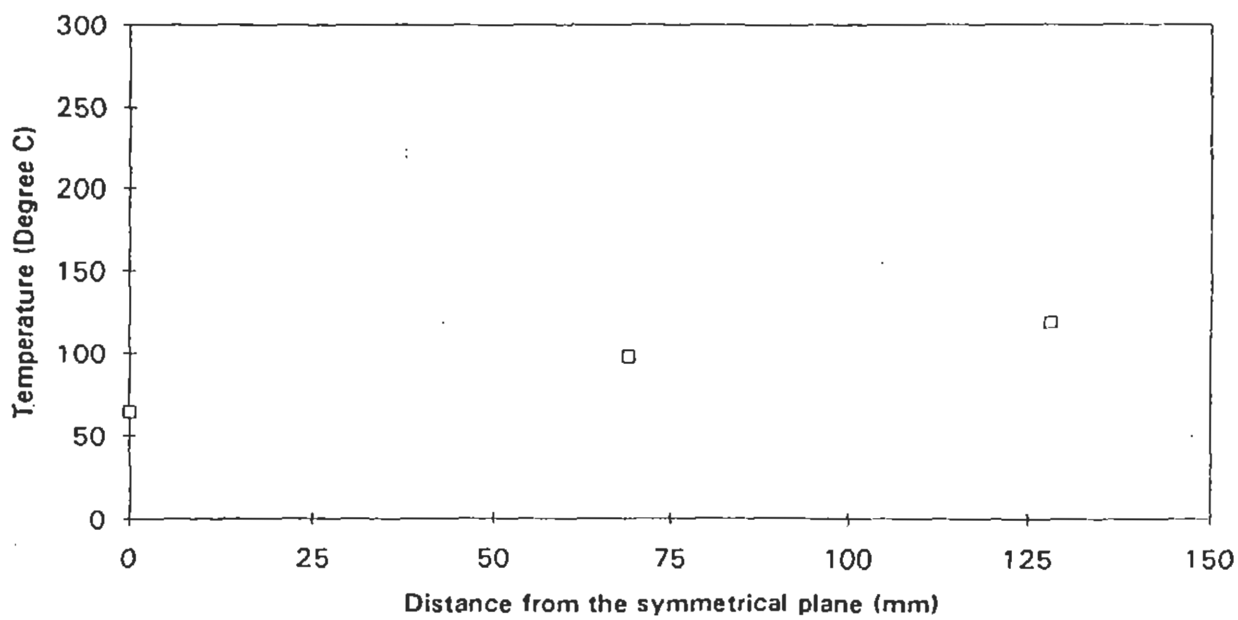


Figure A38: Temperature distribution cross the trench cross-section of plane at x = 500 mm and y = 10 mm.
Trench inclination angle = 30 °
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 6 litres/minute

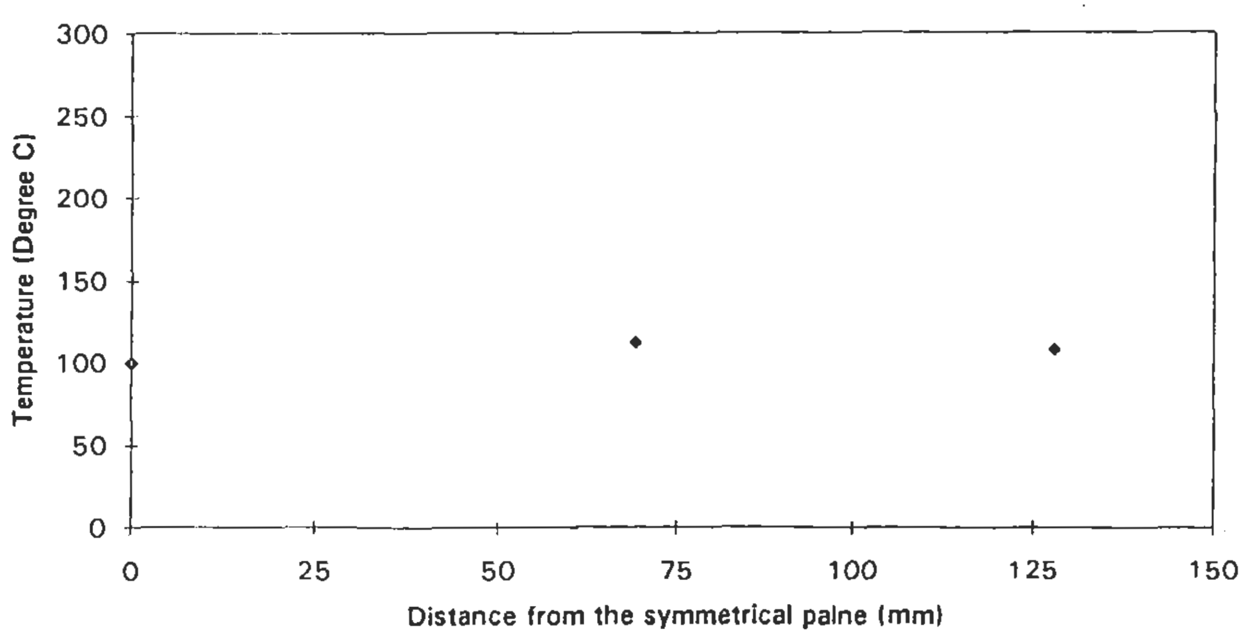


Figure A39: Temperature distribution inside the trench on the symmetrical plane z=0 mm.
Trench inclination angle = 30°
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate =11 litres/minute
The "Top" thermocouple is located 270 mm above the trench floor.
The "Centre" thermocouple is located 140 mm above the trench floor.
The "Bottom" thermocouple is located 10 mm above the trench floor.

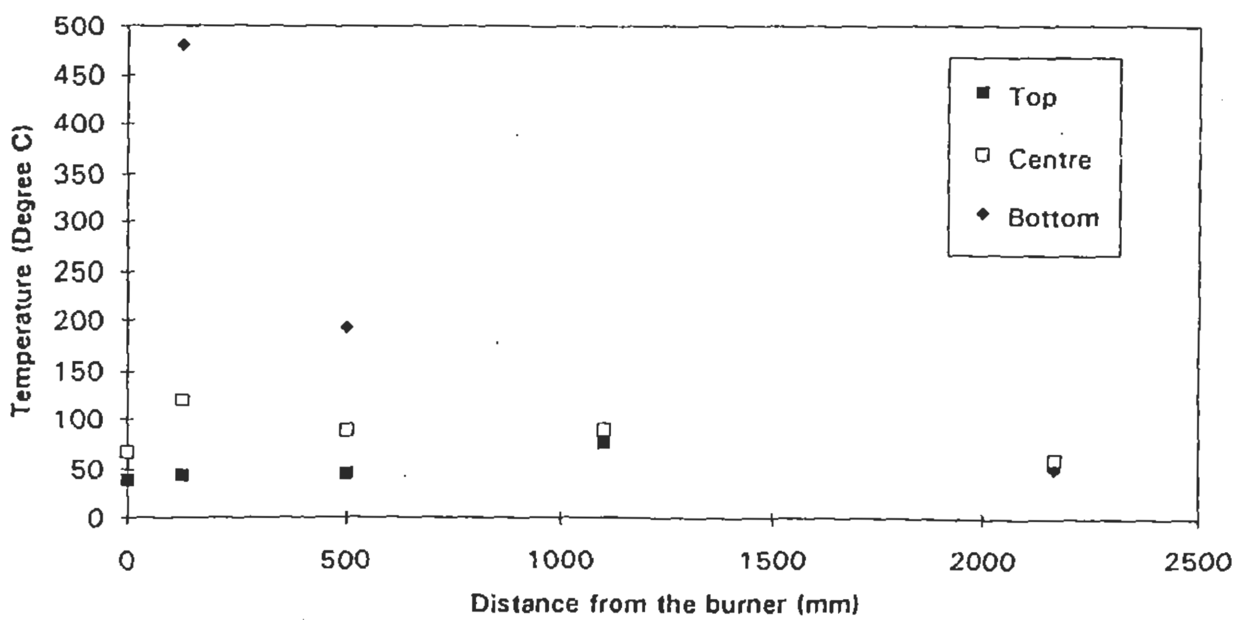


Figure A40: Temperature distribution inside the trench on the plane of z = 69 mm.
Trench inclination angle = 30 °
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 11 litres/minute
The "Top" thermocouple is located 270 mm above the trench floor.
The "Centre" thermocouple is located 140 mm above the trench floor.
The "Bottom" thermocouple is located 10 mm above the trench floor.

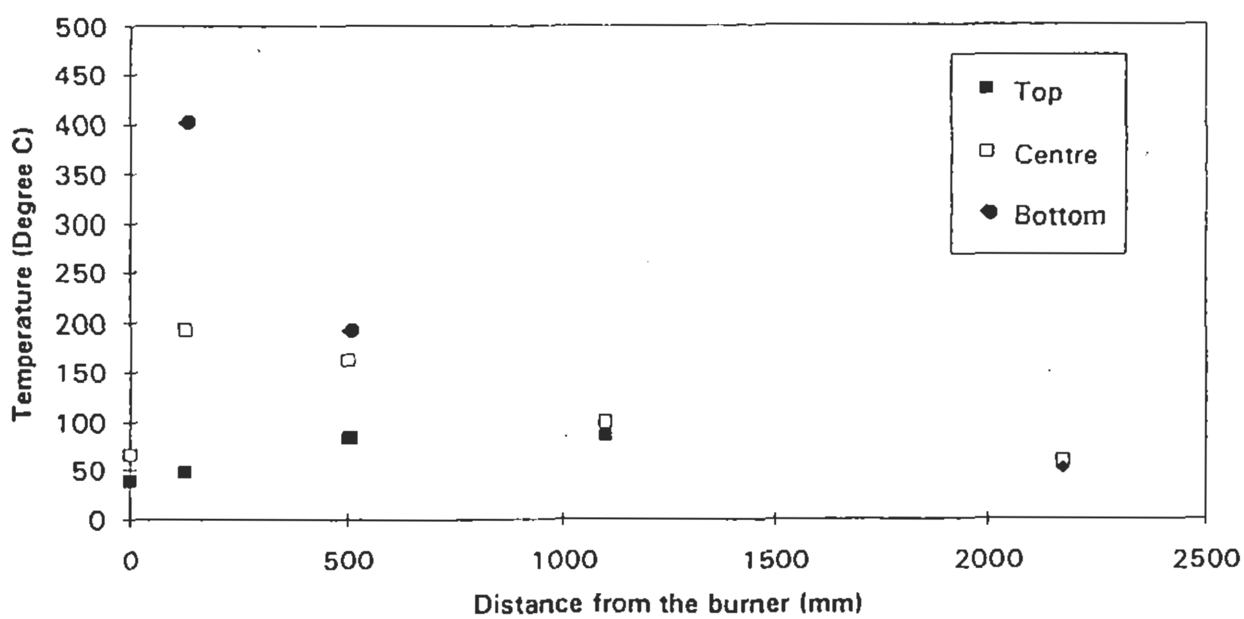


Figure A41: Temperature distribution inside the trench on the plane of z = 128 mm.
Trench inclination angle = 30°
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 11 litres/minute
The "Top" thermocouple is located 270 mm above the trench floor.
The "Centre" thermocouple is located 140 mm above the trench floor.
The "Bottom" thermocouple is located 10 mm above the trench floor.

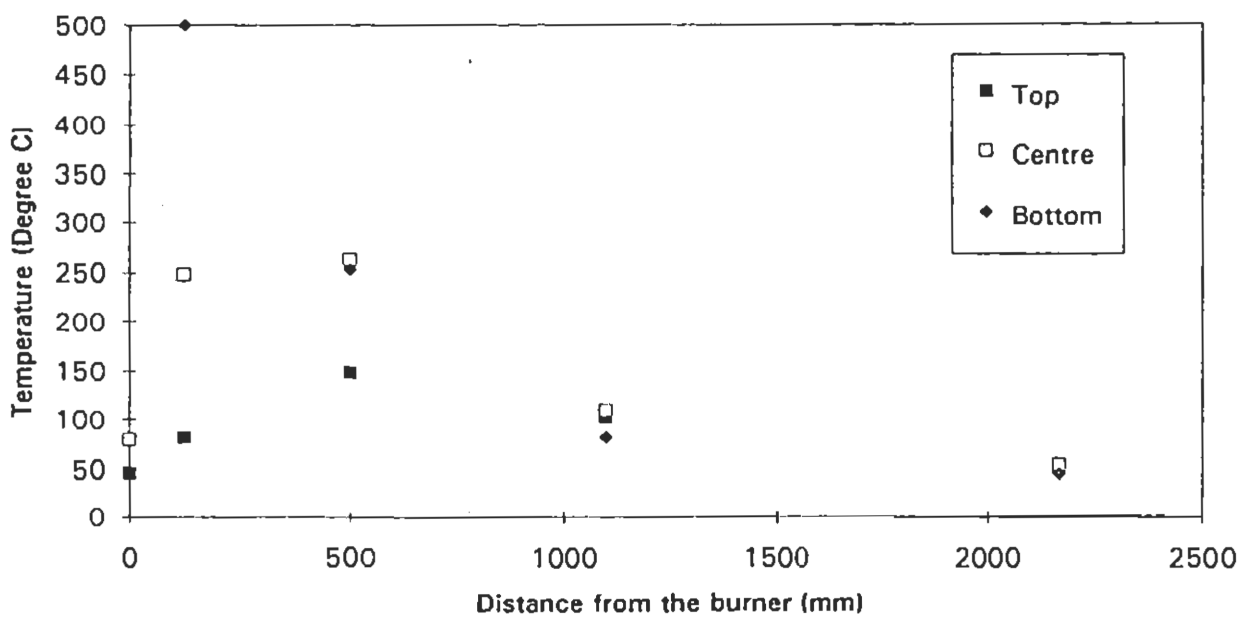


Figure A42: Temperature distribution cross the trench cross-section of plane at x = 125 mm and y = 270 mm.
Trench inclination angle = 30 °
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 11 litres/minute

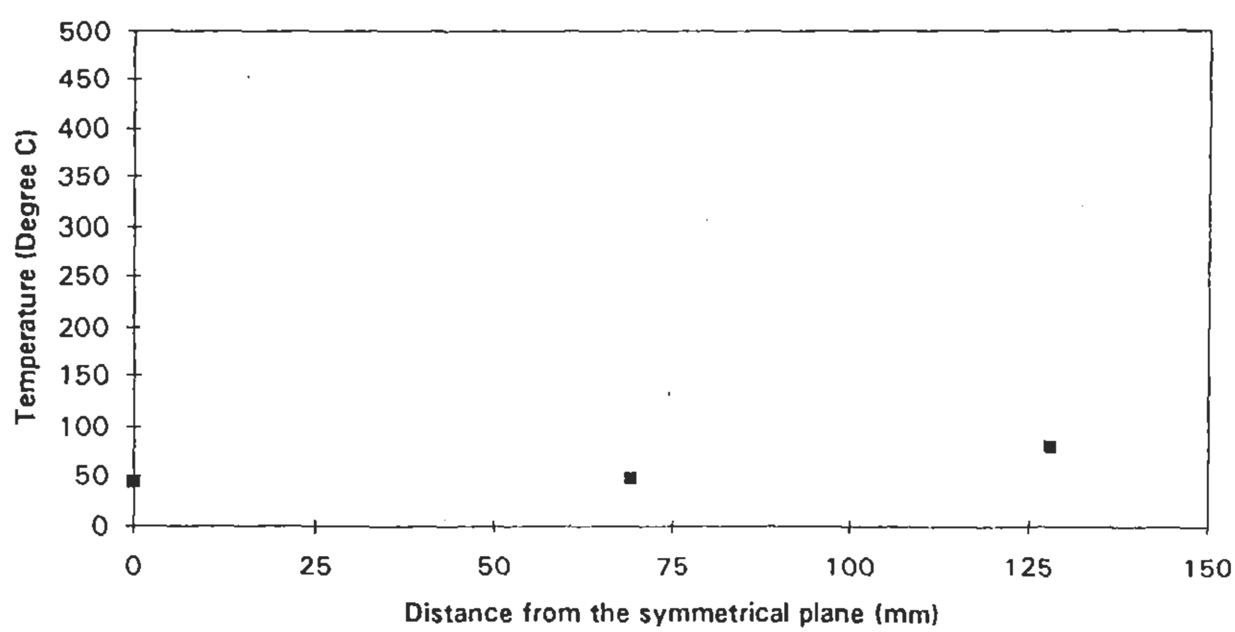


Figure A43: Temperature distribution cross the trench cross-section of plane at x = 125 mm and y = 140 mm.
Trench inclination angle = 30°
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 11 litres/minute

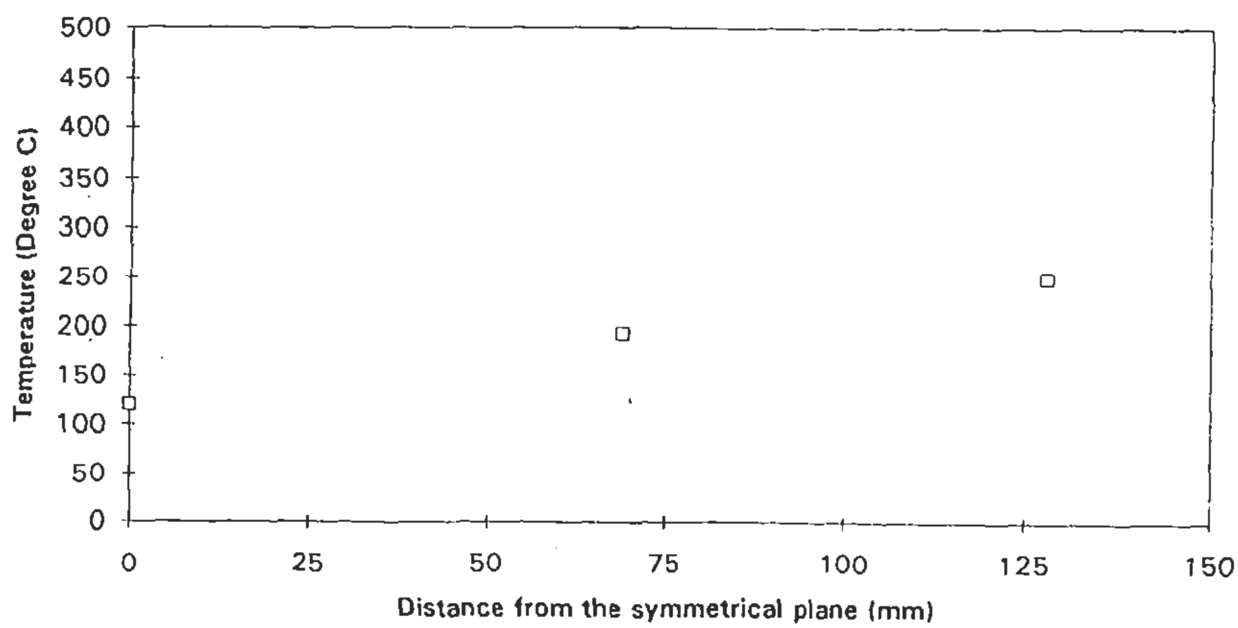


Figure A44: Temperature distribution cross the trench cross-section of plane at x = 125 mm and y = 10 mm.
Trench inclination angle = 30 °
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 11 litres/minute

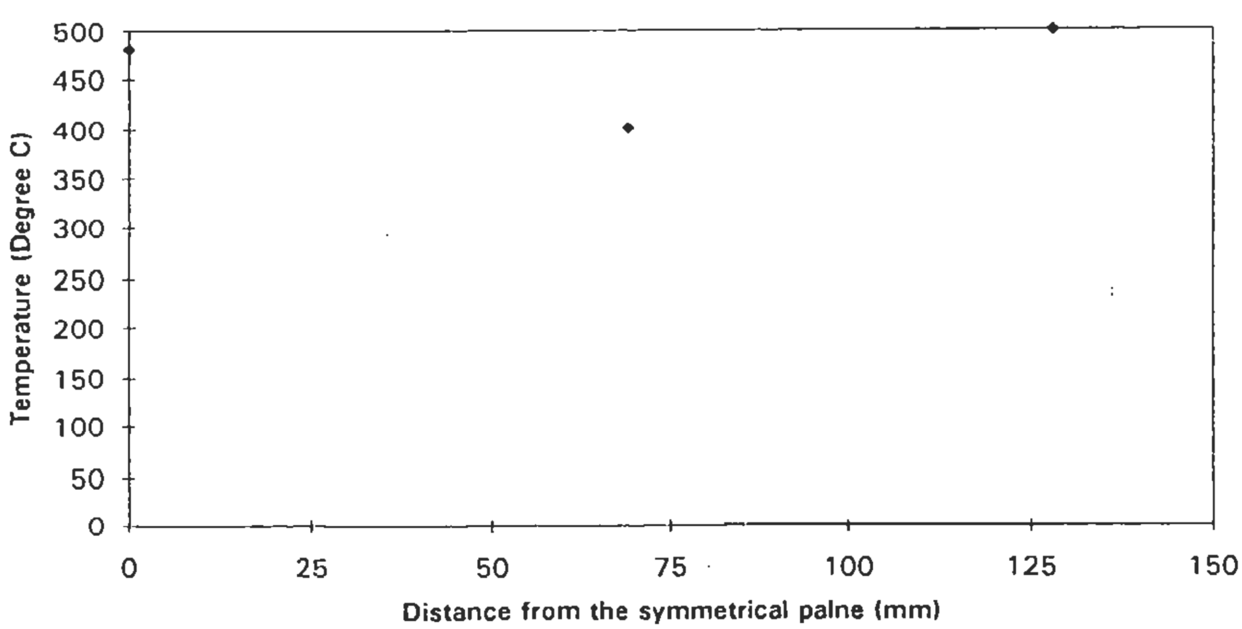


Figure A45: Temperature distribution cross the trench cross-section of plane at x = 500 mm and y = 270 mm.
Trench inclination angle = 30 °
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 11 litres/minute

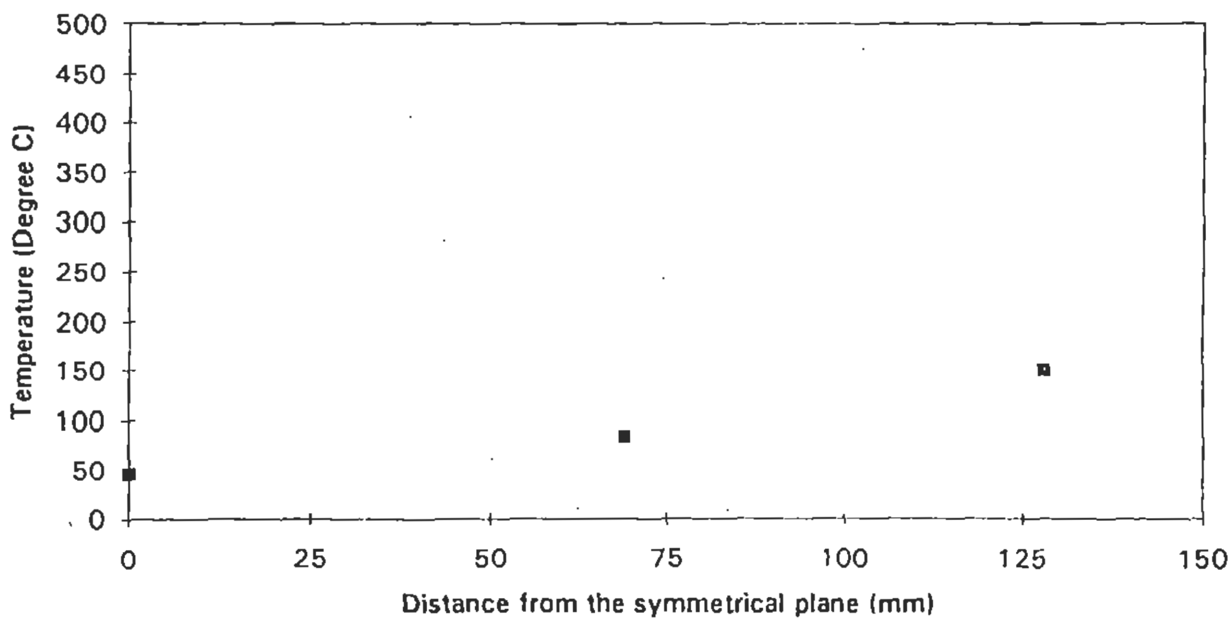


Figure A46: Temperature distribution cross the trench cross-section of plane at x = 500 mm and y = 140 mm.
Trench inclination angle = 30 °
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 11 litres/minute

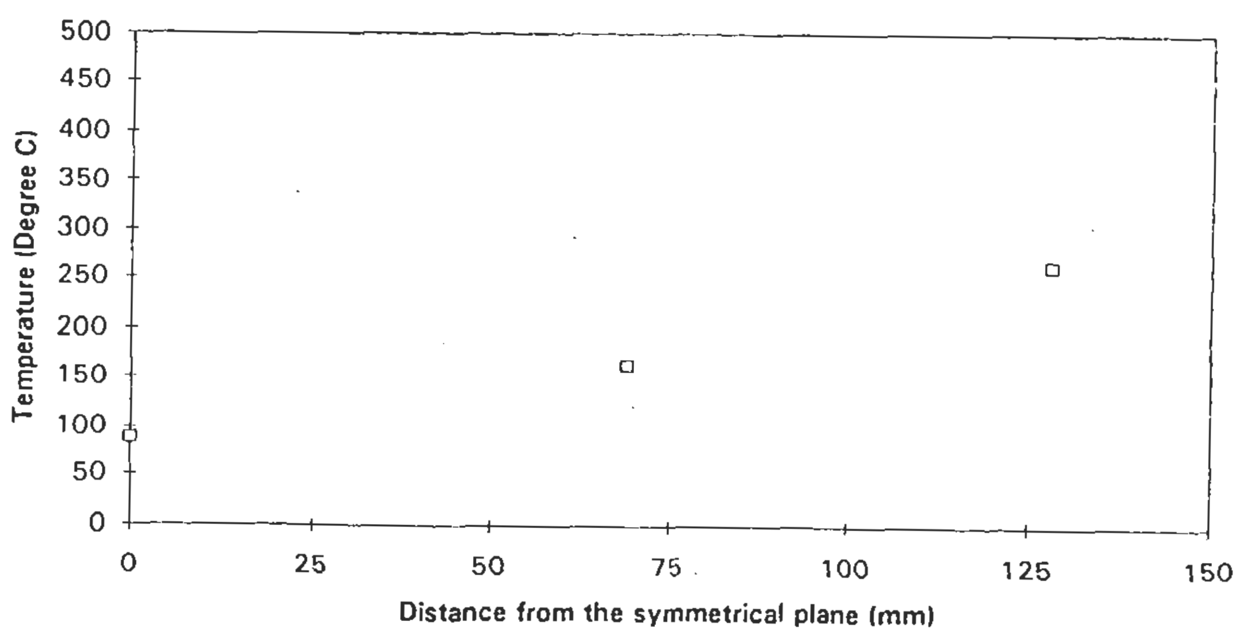


Figure A47: Temperature distribution cross the trench cross-section of plane at x = 500 mm and y = 10 mm.
Trench inclination angle = 30 °
Trench size: 2438 mm L x 276 mm W x 276 mm H
Propane flow rate = 11 litres/minute

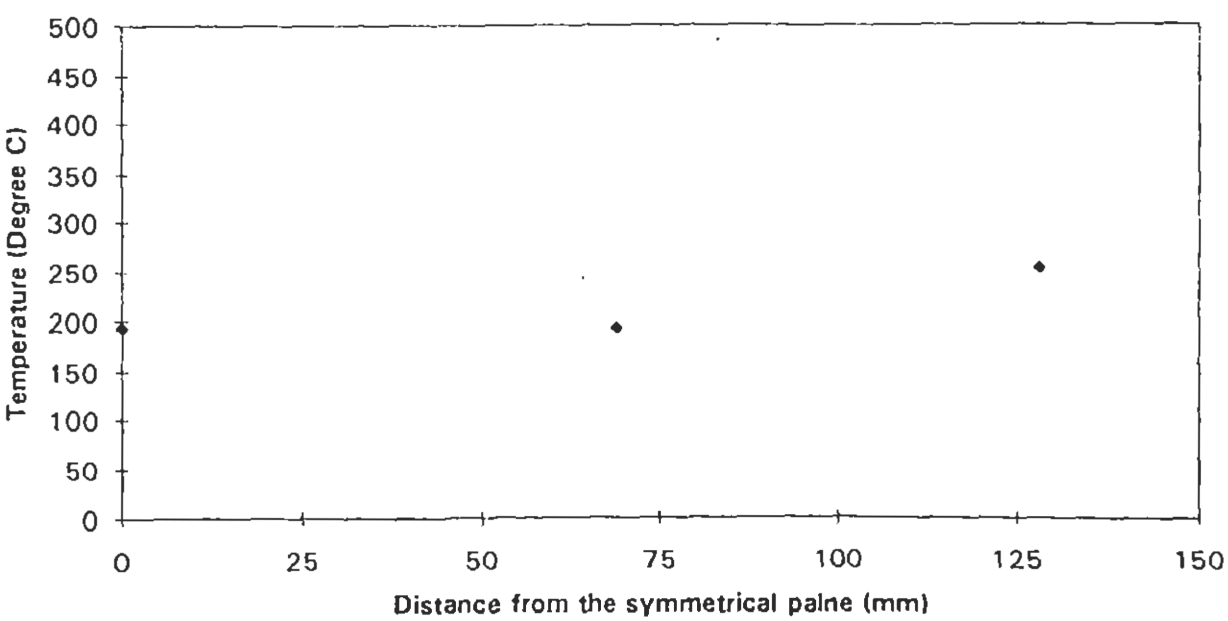


Figure A48: Temperature distribution inside the trench on the plane of z = 0 mm.
Trench inclination angle = 30°
Trench size: 2438 mm L x 92 mm W x 92 mm H
Propane flow rate = 2 litres/minute
The "Top" thermocouple is located 90 mm above the trench floor.
The "Centre" thermocouple is located 48 mm above the trench floor.
The "Bottom" thermocouple is located 5 mm above the trench floor.

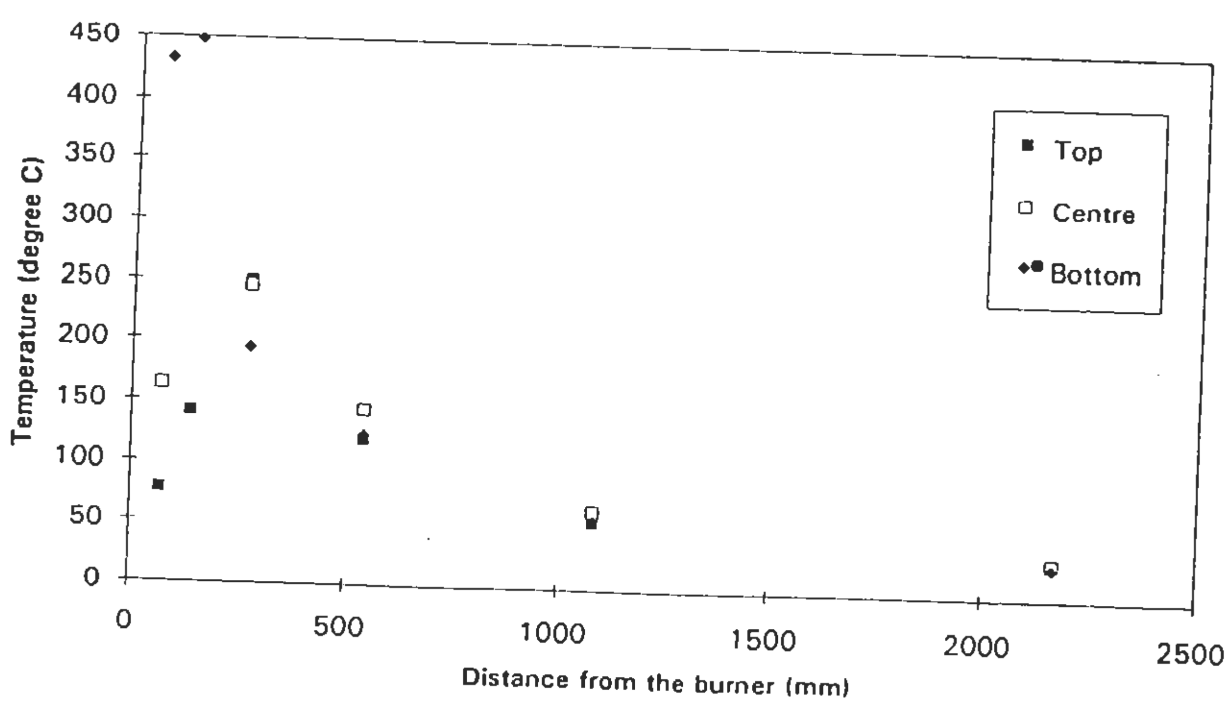


Figure A49: Temperature distribution inside the trench on the plane of z = 23 mm.
Trench inclination angle = 30°
Trench size: 2438 mm L x 92 mm W x 92 mm H
Propane flow rate = 2 litres/minute
The "Top" thermocouple is located 90 mm above the trench floor.
The "Centre" thermocouple is located 48 mm above the trench floor.
The "Bottom" thermocouple is located 5 mm above the trench floor.

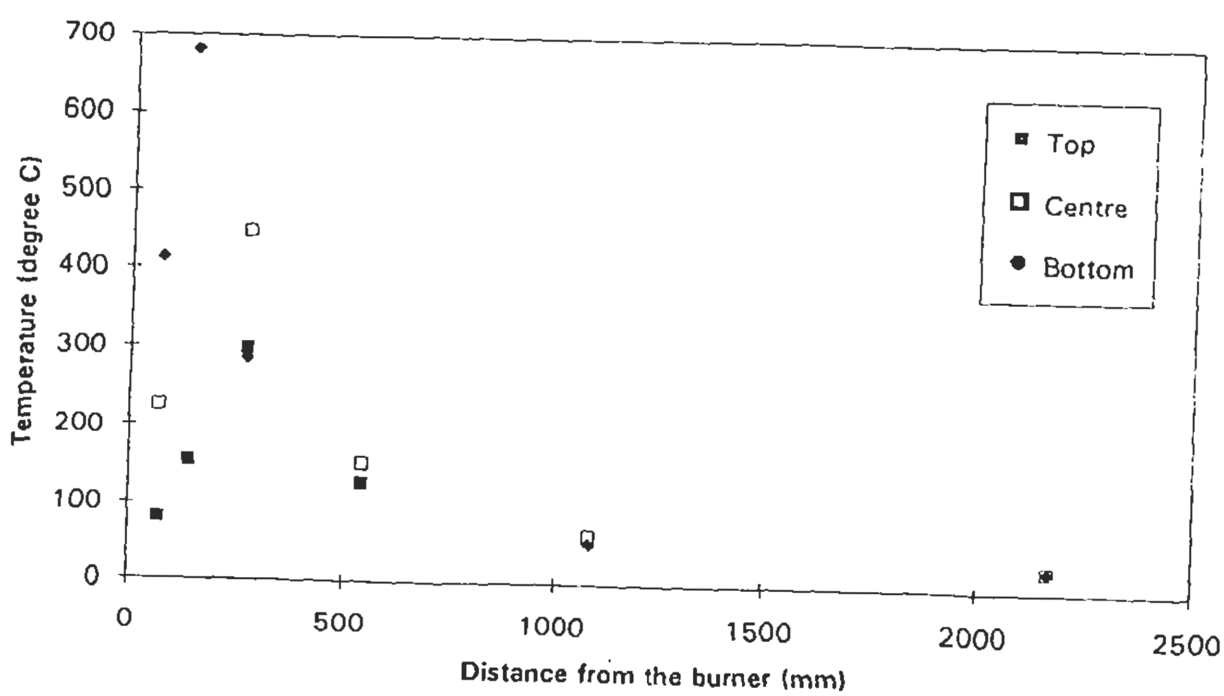


Figure A50: Temperature distribution inside the trench on the plane of z = 0 mm.
Trench inclination angle = 30°
Trench size: 2438 mm L x 92 mm W x 92 mm H
Propane flow rate = 6 litres/minute
The "Top" thermocouple is located 90 mm above the trench floor.
The "Centre" thermocouple is located 48 mm above the trench floor.
The "Bottom" thermocouple is located 5 mm above the trench floor.

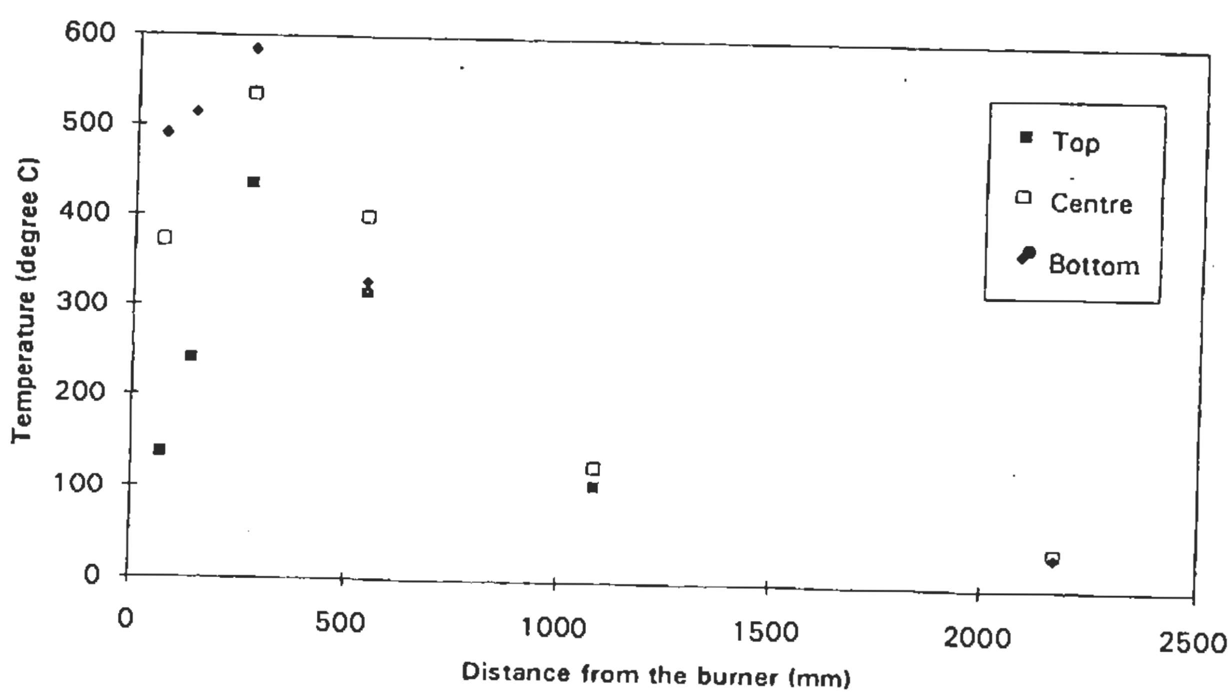


Figure A51: Temperature distribution inside the trench on the plane of z = 23 mm.
Trench inclination angle = 30°
Trench size: 2438 mm L x 92 mm W x 92 mm H
Propane flow rate = 6 litres/minute
The "Top" thermocouple is located 90 mm above the trench floor.
The "Centre" thermocouple is located 48 mm above the trench floor.
The "Bottom" thermocouple is located 5 mm above the trench floor.

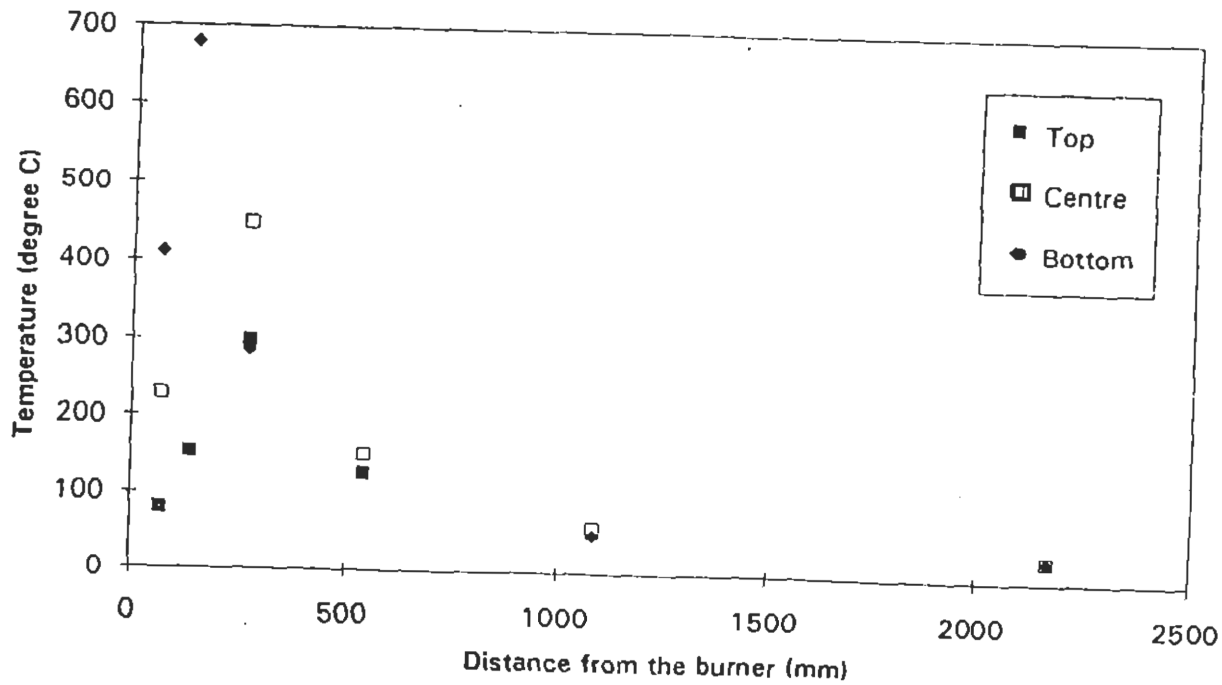


Figure A52: Temperature distribution inside the trench on the plane of z = 0 mm.
Trench inclination angle = 30°
Trench size: 2438 mm L x 92 mm W x 92 mm H
Propane flow rate = 11 litres/minute
The "Top" thermocouple is located 90 mm above the trench floor.
The "Centre" thermocouple is located 48 mm above the trench floor.
The "Bottom" thermocouple is located 5 mm above the trench floor.

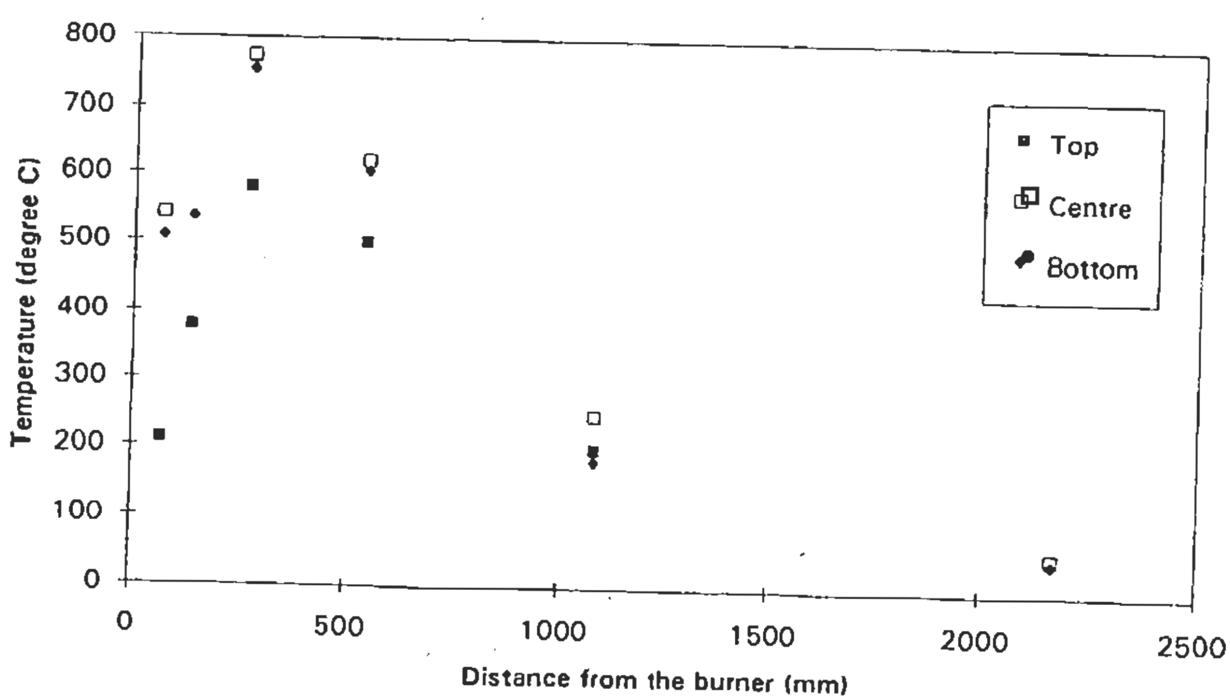
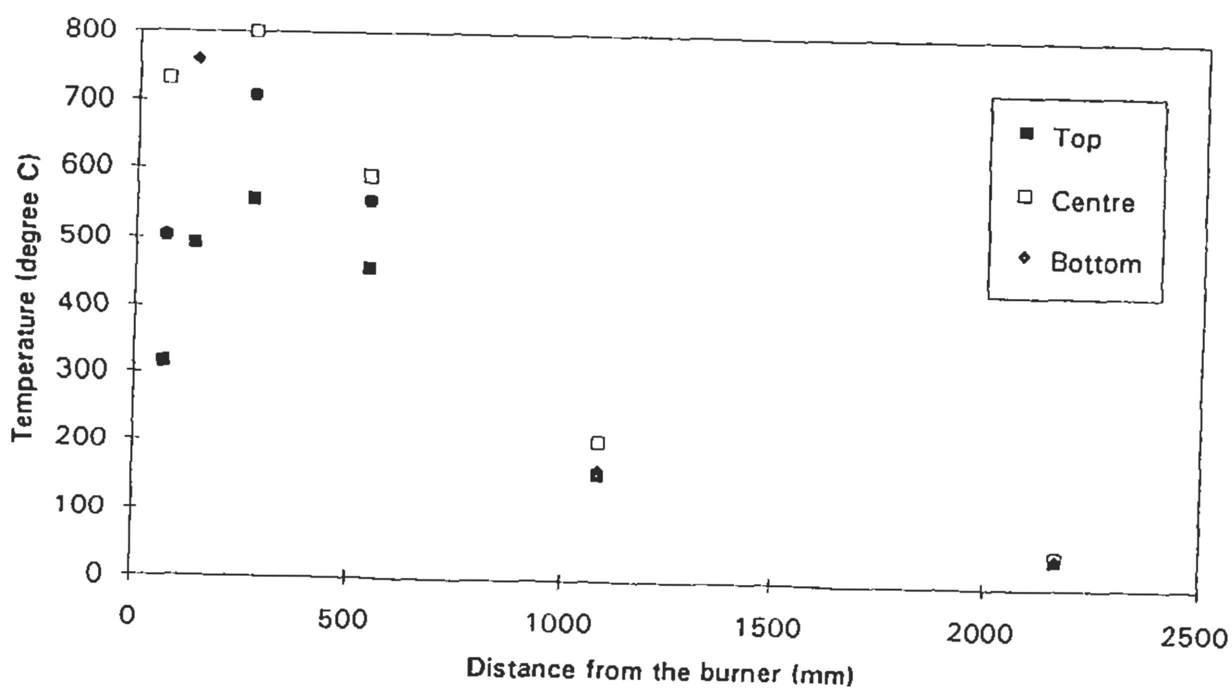


Figure A53: Temperature distribution inside the trench on the plane of z = 23 mm.
Trench inclination angle = 30°
Trench size: 2438 mm L x 92 mm W x 92 mm H
Propane flow rate = 11 litres/minute
The "Top" thermocouple is located 90 mm above the trench floor.
The "Centre" thermocouple is located 48 mm above the trench floor.
The "Bottom" thermocouple is located 5 mm above the trench floor.



Appendix B

The CFD Simulation Results

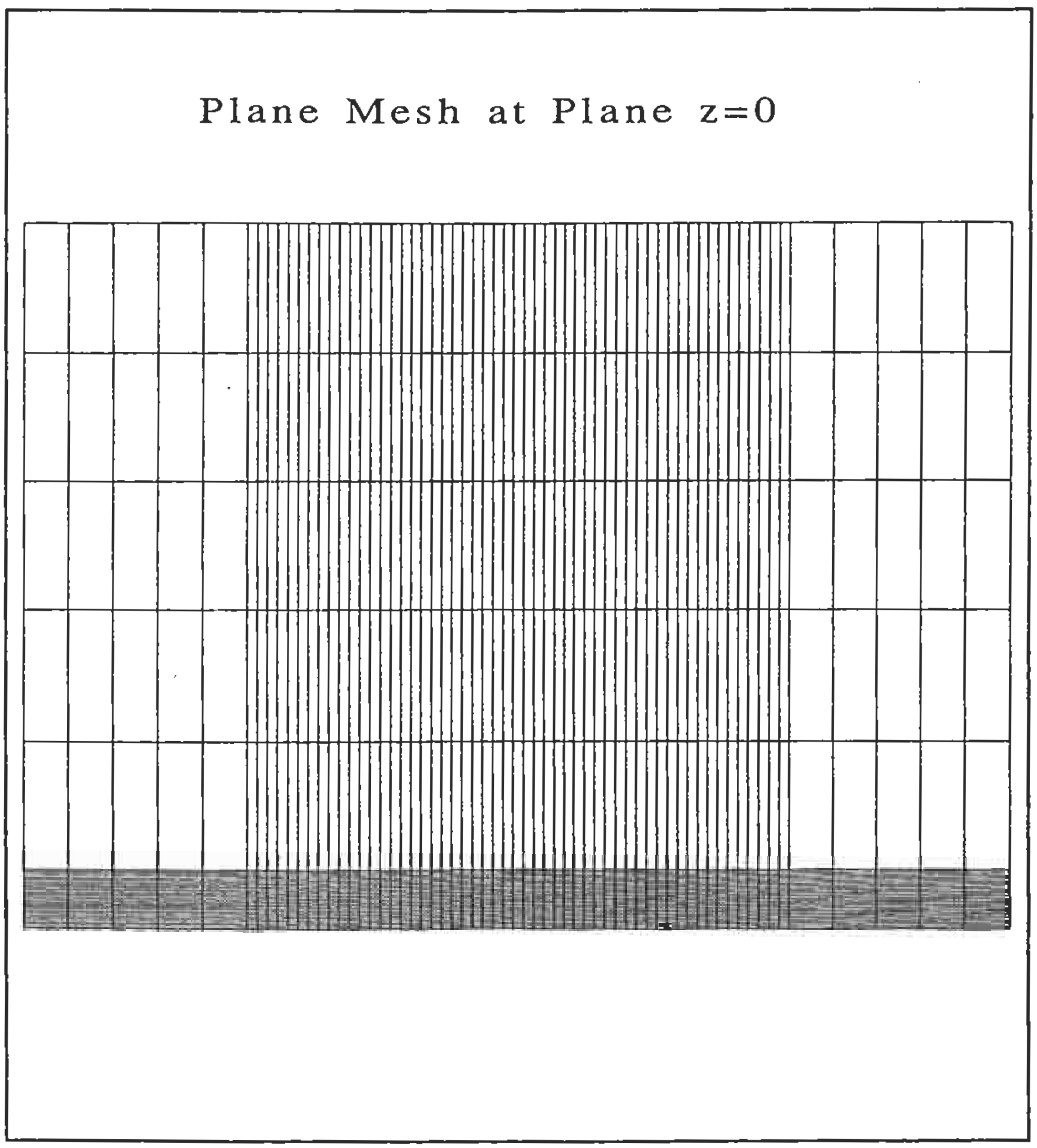


Figure B1

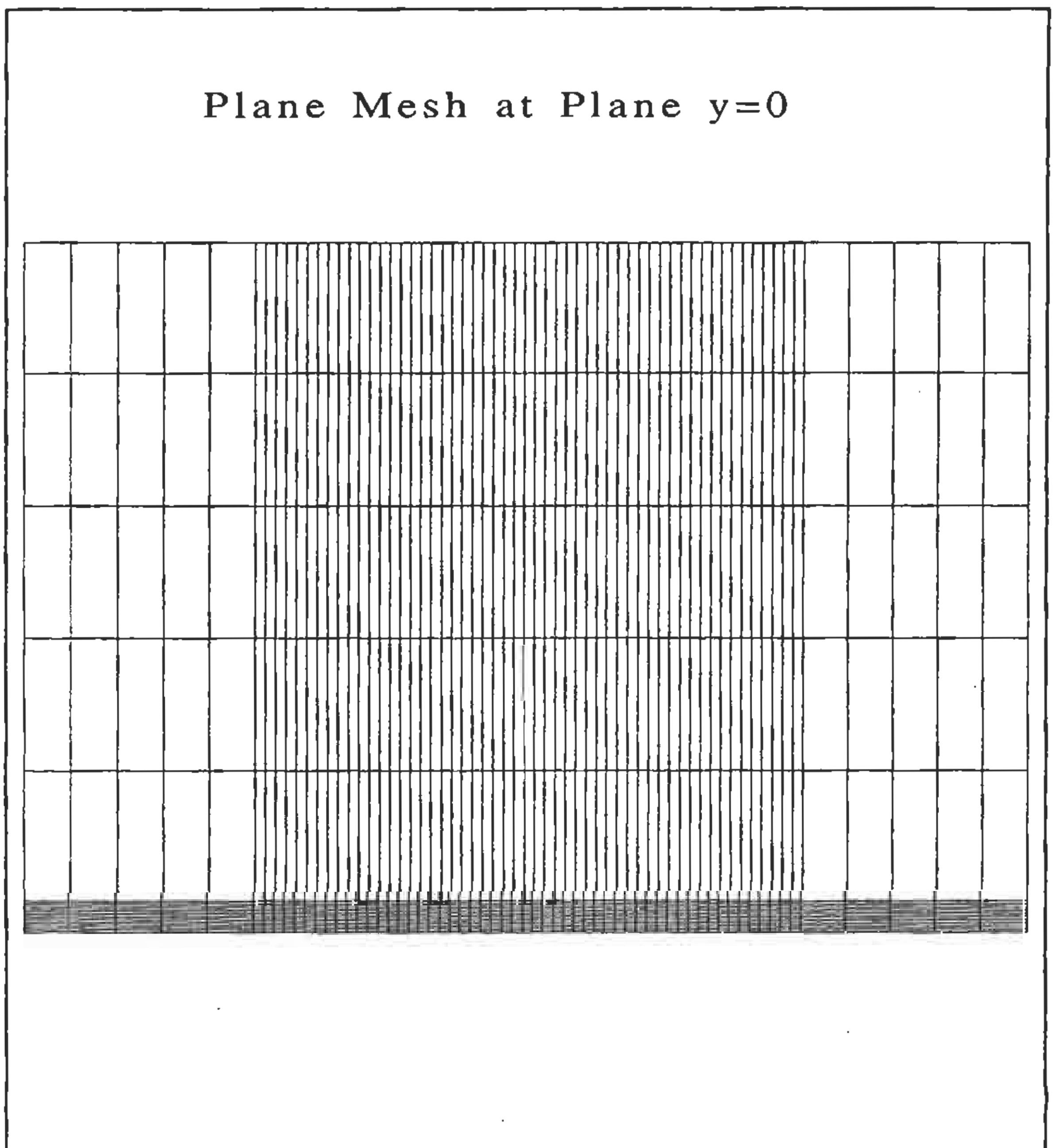


Figure B2

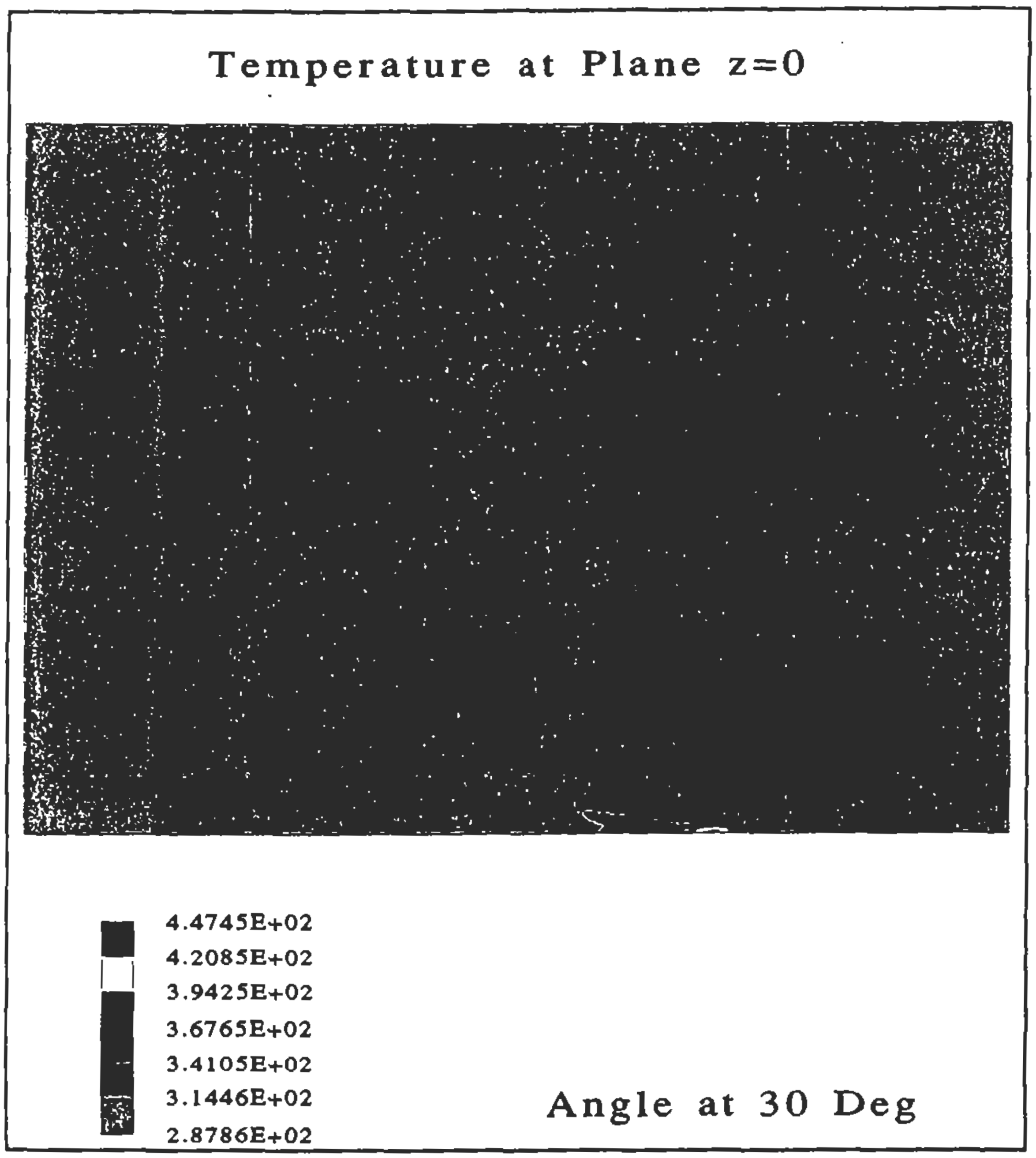

Temperature at Plane z=0
4.4745E+02
4.2085E+02
3.9425E+02
3.6765E+02
3.4105E+02
3.1446E+02
2.8786E+02
Angle at 30 Deg

Figure B3

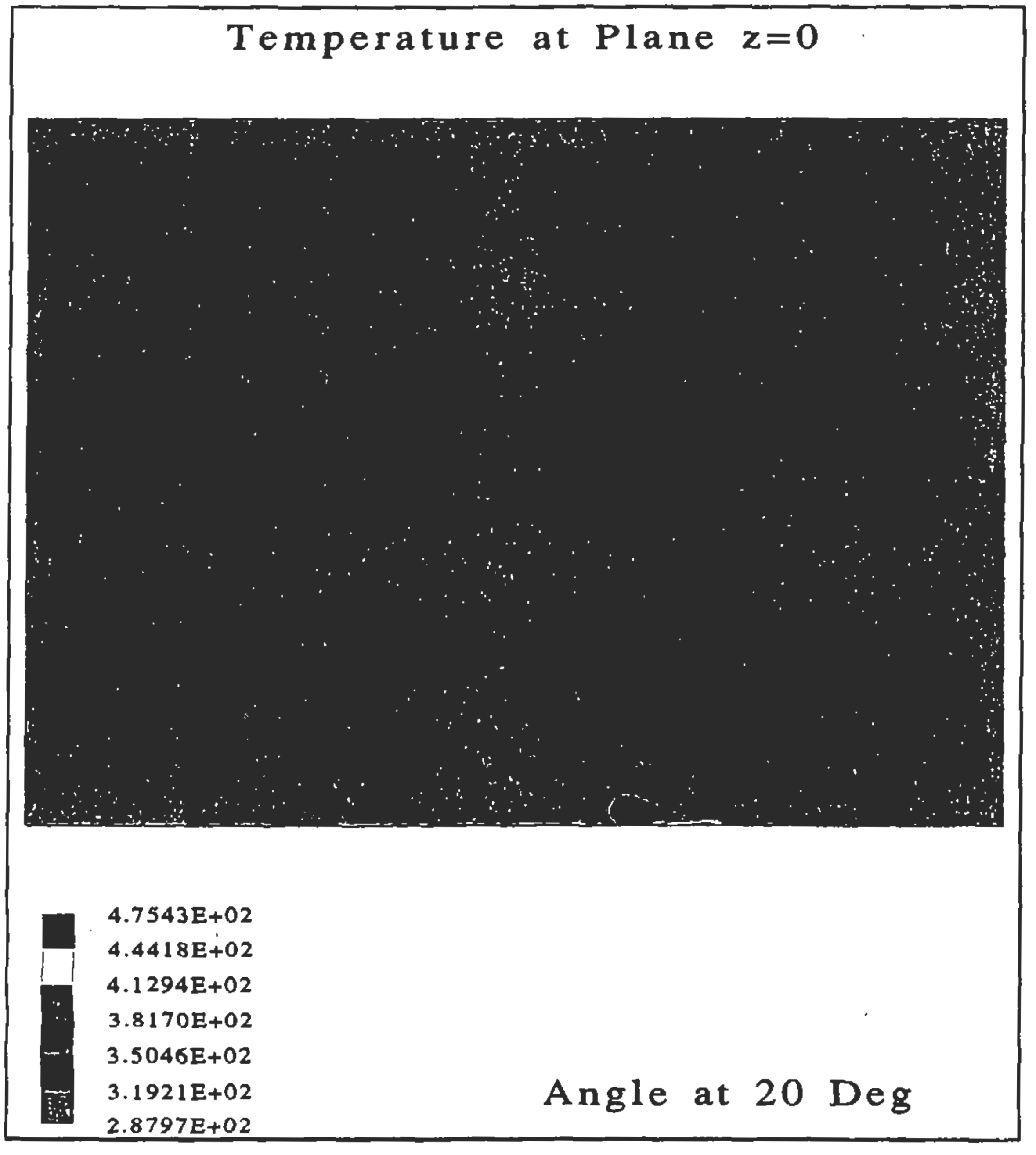
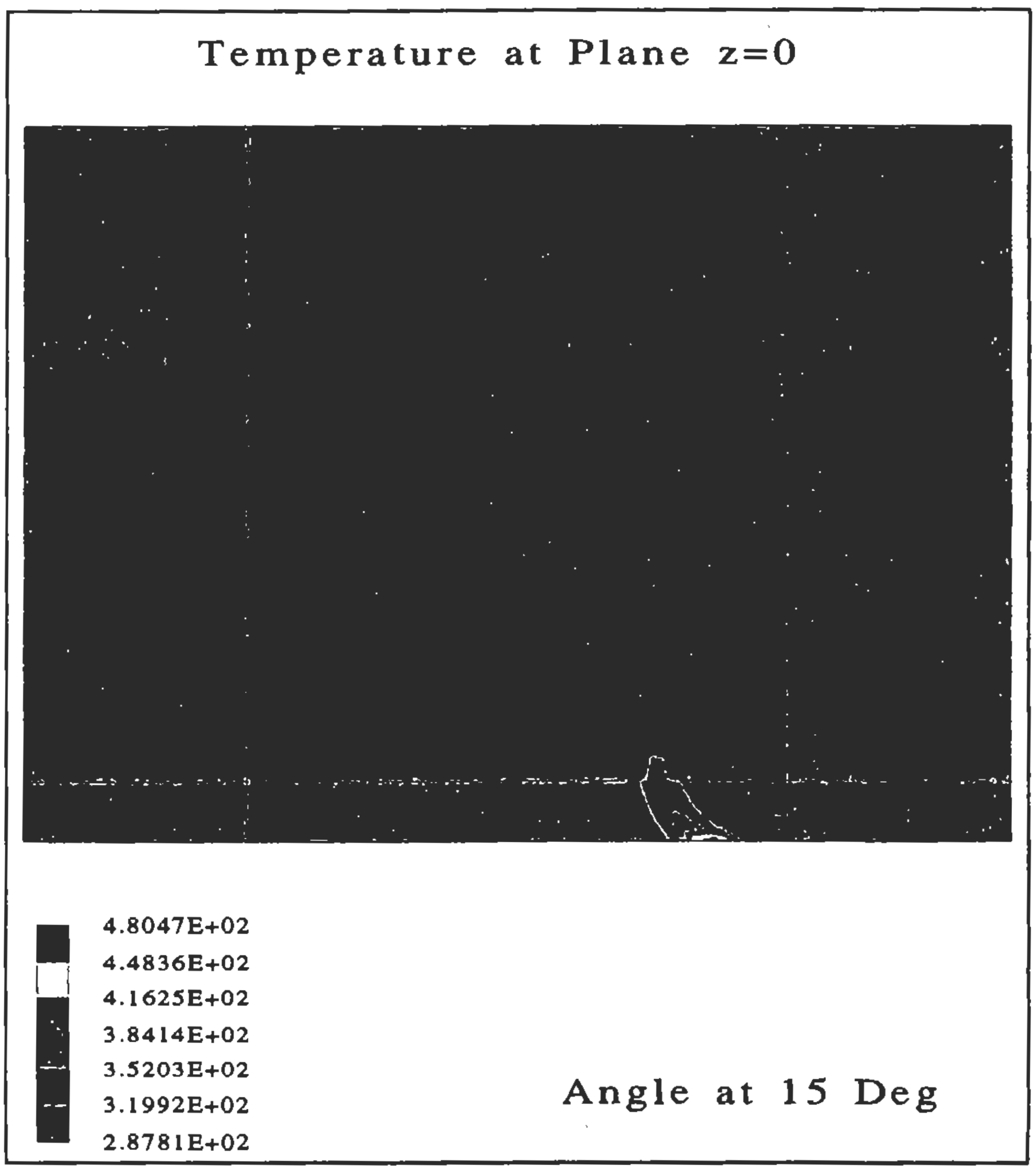

Temperature at Plane z=0
4.7543E+02
4.4418E+02
4.1294E+02
3.8170E+02
3.5046E+02
3.1921E+02
2.8797E+02
Angle at 20 Deg

Figure B4



Temperature at Plane z=0
4.8047E+02
4.4836E+02
4.1625E+02
3.8414E+02
3.5203E+02
3.1992E+02
2.8781E+02
Angle at 15 Deg

Figure B5

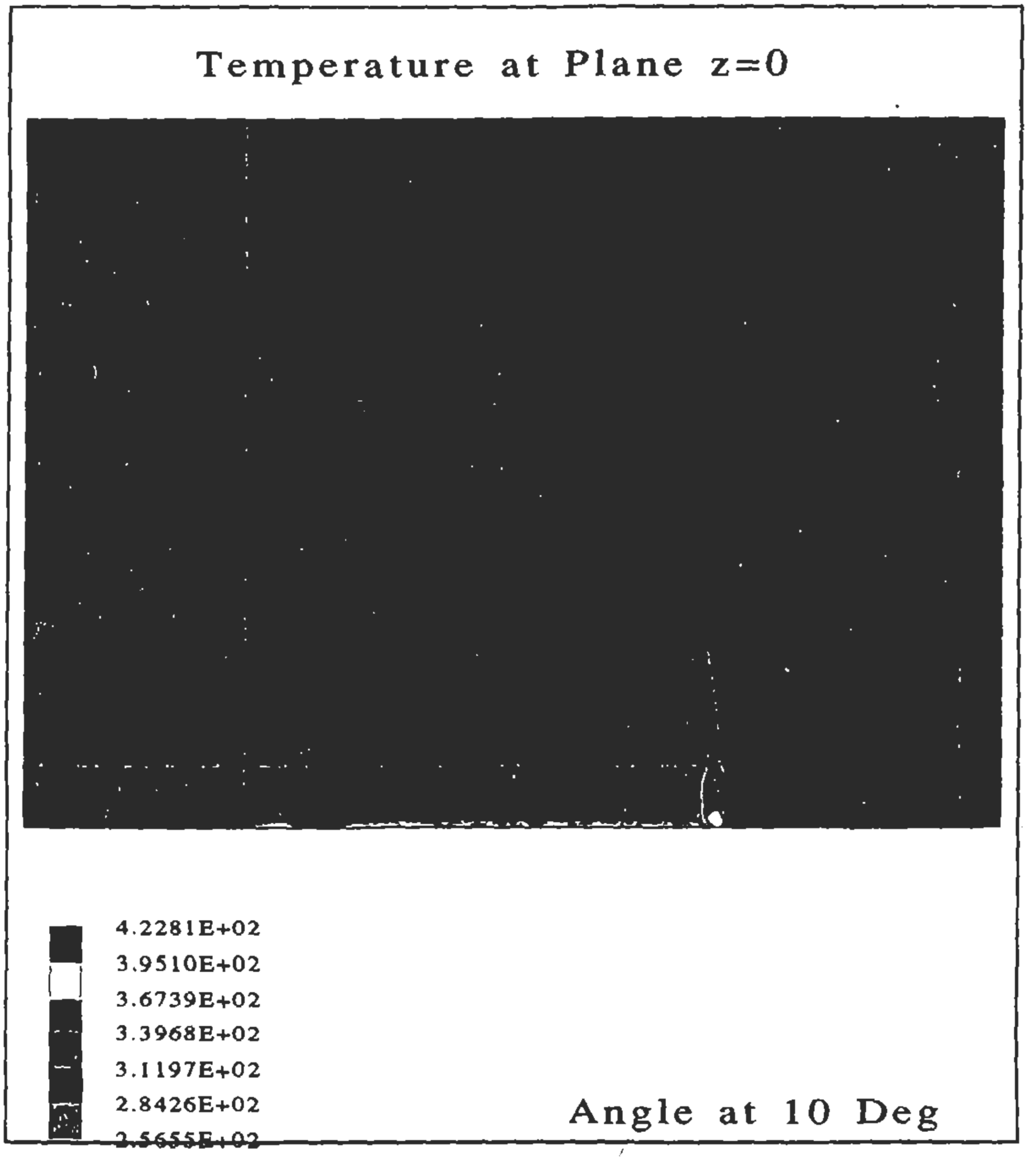

Temperature at Plane z=0
4.2281E+02
3.9510E+02
3.6739E+02
3.3968E+02
3.1197E+02
2.8426E+02
2.5655E+02
Angle at 10 Deg

Figure B6

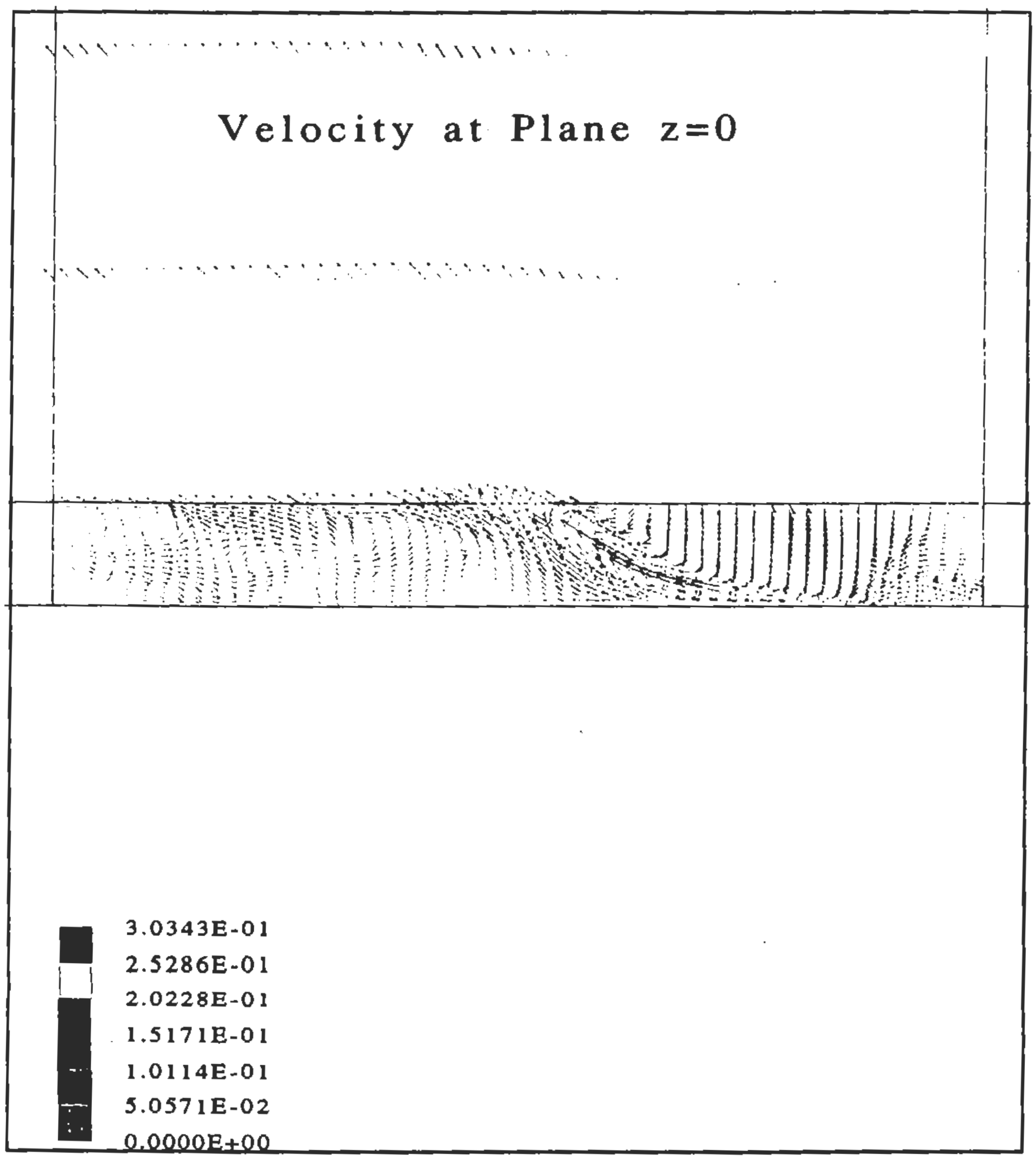

Velocity at Plane z=0
3.0343E-01
2.5286E-01
2.0228E-01
1.5171E-01
1.0114E-01
5.0571E-02
0.0000E+00

Figure B7

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