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UNIVERSITY OF ALBERTA

HEAT FLUX MEASUREMENTS IN A CUBICAL COMBUSTION CELL

BY

MING JIANG ©

A THESIS SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

DEPARTMENT OF MECHANICAL ENGINEERING
EDMONTON, ALBERTA
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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled HEAT FLUX MEASUREMENTS IN A CUBICAL COMBUSTION CELL submitted by Ming Jiang in partial fulfilment of the requirements for the degree of Master of Science.

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ABSTRACT

Combustion cells are used to study ignition processes and flame growth under a variety of initial conditions. One goal of these studies is to develop models of flame growth so that burning velocities can be predicted knowing the initial conditions. Most models assume adiabatic conditions which leads to erroneous predictions of burning speeds. In order to correct a model for heat losses, measurements of the heat transfer to the combustion cell walls are necessary.

In this study, experimental measurements of pressure, wall temperature, and wall heat flux were obtained for laminar and turbulent explosions of premixed methane-air mixtures in a cubical combustion cell. A thin platinum film resistance thermometer heat flux gauge was used to measure the transient wall temperature from which the wall heat fluxes were calculated using Duhamel's theorem. Turbulence in the cell was generated by pulling a 60% solid, perforated plate across the chamber prior to the spark discharge. The turbulence intensity was controlled by varying the plate speed and the time delay before spark ignition. Turbulence intensity at ignition was up to 3m/s with a integral scale of 4mm. The experiments were performed over a range of equivalence ratios from 0.6 to 1.0.

Results from the experiments show that: 1) The heat flux

to the wall increases gradually before flame contact; then increases sharply [illegible] flame reaches the wall. 2) The peak value of the heat flux varies considerably with equivalence ratio and the initial turbulence intensity. The higher the equivalence ratio and initial turbulence intensity, the higher the peak value. 3) The measurements of burning velocities are underpredicted when heat losses are not taken into account.

Based on the measurements, correlations were developed for heat transfer to the wall before flame arrival. The heat transfer was found to be dependent on the turbulent intensity at the time of spark discharge.

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A most special thank you and sincere appreciaton go to my parents and my husband. Without their supprot and love, this work would not have been possible.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

A	Area
b	Combustion chamber type constant
c	Specific heat
c_1, c_2,..	Coefficients and exponents
C	Piston speed
C_1, C_2	Constant
d	Cylinder diameter
D	Plate hole diameter
h	Heat transfer coefficient
k	Thermal conductivity
l	Thickness
L	Length
M	Mach number
Nu	Nusselt number
p	Pressure
q	Wall heat flux
Q	Transferred heat
R	Bomb radius
Re	Reynolds number
Su	burning velocity
t	Time
T	Temperature
u	Fluctuation component of velocity

u'	RMS intensity
u_o'	Initial turbulence intensity
U	Mean component of velocity
V	Cylinder volume
w	Width
x	Distance perpendicular to the wall
X	Downstream distance
ϵ	Emissivity
σ_0	Stefan-Boltzmann constant
τ_r	Characteristic response time
ρ	Density
α	Thermal diffusivity
γ	Specific heat ratio
Λ	Integral length scale
ν	Kinematic viscosity

Subscripts

b	Backing material
c	Convection
d	Downstream
f	Film
init	Initial
m	Mean
r	Radiation
t	Turbulent

u	unburned
w	wall

CHAPTER 1

INTRODUCTION

Combustion cells are used to study ignition processes and flame propagation rates in quiescent mixtures and those with turbulence. Burning velocities in homogeneous mixtures in cells can be determined by using high speed photography, ionization probes and pressure based diagnostics. The latter is most common because of its ease of application. Calculating the burning velocity from the pressure data is not straight forward because the temperature of the burned gases as a function of time must be calculated. Assuming adiabatic conditions will lead to erroneous results because heat losses occur from the compressed unburned gases and the flame to the walls of the cell. This suggests the need for basic experimental heat transfer studies in combustion cells.

Experimental heat transfer measurements in combustion chambers have been made for many years (e.g. Nusselt, 1923). Because of complexities of combustion arising from variable pressure and temperature, chemical reactions, complex flow patterns and high temperatures, the heat transfer to the walls of a combustion chamber depends upon many factors, some of which are still not thoroughly understood. A detailed model of the heat transfer in a combustion chamber based on a knowledge of the physical process involved would require a fundamental understanding of some of the following complicated phenomena: the ignition process, the dynamics of turbulent flames, and the interaction of the compressed unburned gases and the flame with the cold walls.

Many of the aforementioned phenomena have been studied separately in order to obtain a basic understanding [Afgan&Beer, 1974; Hoult, Hamiroune, and Keck, 1986; Vosen, 1983]. The purpose of this work was to conduct heat flux measurements and to develop correlations to predict the heat transfer during the compressed unburnt gas - wall interactions in a turbulent combustion cell. The results are to be used for correcting burning velocity predictions for heat losses.

1.1 Experimental Study of Wall Heat Transfer

The interactions of the end gas and the flame with cold walls have been studied in an attempt to understand internal combustion engines as well as other systems. Experimental data for combustion from the end walls of shock tubes, in fired internal combustion engines, and in constant volume combustion chambers are available. Meperkan(1980) performed an experimental and theoretical study of wall heat transfer for combustion in a shock tube. This was done to examine the effects of kinetics and nonequilibrium conditions on the heat transfer. Overbye, et al.(1961) obtained wall heat flux data in spark ignition engines including a study of the effect of deposits on the combustion chamber wall. Yoshida, Harigaya, and Miyazaki (1980) obtained heat flux measurements to the piston of a pre-chamber type diesel engine, which studied the effect of the inlet jet flow. Alkidas and Cole (1981) investigated the transient heat flux and heat rejection to the coolant in a divided chamber diesel engine. Most of the data from engines include many of the complexities relating to overall effects and performance of the system. It is therefore difficult to utilize these data to study the specific, localized phenomena; e.g. flame wall interactions, etc. Isshiki & Nishiwaki(1974) and Vosen(1983) measured and correlated the unsteady heat transfer in a constant volume combustion chamber. In both studies, heat transfer measurements were made for one dimensional flames for a variety of pressures. In Woodard's study [Woodard, 1982], measurements of the heat transfer were made in a two dimensional system, and were related to the flame positions(from photographs) and the pressure in the system.

Few data are available for heat transfer in turbulent combustion cells. Moult, Namiroune, and Keck(1987) measured and correlated the heat transfer in a turbulent combustion bomb for one equivalence ratio and three levels of initial turbulence. There is a pressing need for more data, in particular, data on end gas - wall and flame - wall interactions for different levels of initial turbulence and different equivalence ratios.

In this study, simultaneous data on pressure, wall temperature, and wall heat flux for explosions of homogeneous air-methane mixtures in a cubical cell are obtained. In particular, the dependence of the wall heat flux on equivalence ratio and initial turbulence intensity is analyzed. Combustion near the lean limit is compared with stoichiometric results. The experimental apparatus used in this work is described in Chapter 2 and Chapter 3. The experimental measurements and the heat flux results are provided and discussed in Chapter 4.

1.2 The Development of Heat Transfer Correlations

Correlations of heat transfer in internal combustion engines have existed for some years. A number of authors have tackled this problem [Nusselt,1923; Briling,1931; Eichelberg, 1939; Pflaum,1962; Annand,1963], and these theoretical and experimental investigations have produced various formulae for the heat transfer coefficient in the engines as listed in Table 1.1:

Table 1.1

Formulas for the heat transfer coefficients in engines

Formula	Proposed by
$h = 0.99(1 + 1.24\,c_m)(\sqrt[3]{p^2T})$	Nusselt
$h = 0.99(3.5 + 0.185 \times c_m)(\sqrt[3]{p^2T})$	Briling
$h = 2.1(\sqrt[3]{c_m})(\sqrt{pT})$	Eichelberg
$h = f_1(p) \times f_2(c_m) \times \sqrt{pT}$	Pflaum
$h = 0.49(\frac{k}{d})Re^{0.7} + 0.91 \times \frac{[(\frac{T}{100})^4 - (\frac{T_w}{100})^4]}{T - T_w}$	Annand

where: $h =$ heat transfer coefficient

$c_m =$ mean piston speed

$p =$ gas pressure

$T =$ local mean gas temperature

$k =$ thermal conductivity

$d =$ cylinder bore

$T_w =$ wall temperature

However, as pointed out by Woschni (1967), when being applied to a given engine, these formulas give results that differ as much as 200%. Woschni proposed a universally applicable equation for the instantaneous heat transfer coefficient in the internal combustion Engines as following:

$$h = 110d^{-0.2}p^{0.8}T^{-0.53}[C_1 c_m + C_2\frac{V_s T_1}{p_1 V_1}(p - p_0)]^{0.8}.$$

or

$$N_u = 0.035Re^{0.8}$$

where: C_1, C_2 = constant
V_s = cylinder volume
V_1 = instantaneous cylinder volume
p_1, T_1 = known state of the working gas related to V_1
p_0 = gas pressure in the cylinder of the corresponding motored engine
N_u = Nusselt number
Re = Reynolds number

It contains two convective terms. One of them takes into account the piston motion, and the other the convection due to combustion. Using a power of 0.8 for Reynolds number and taking radiation as part of the convective term made it deficient in scientific approach, as pointed out by Sitkei and Ramanaiah (1972). Sitkei and Ramanaiah (1972) proposed a newer equation for calculating instantaneous heat transfer in engines as following:

$$\begin{aligned} Q &= Q_c + R_r \\ &= \sum 0.04(1+b)\frac{p^{0.7}c_m^{0.7}}{T^{0.2}de^{0.3}}A(T - T_w)t \ + \ \sum \epsilon\sigma_0 A[(\frac{T_f}{100})^4 - (\frac{T_w}{100})^4]t \end{aligned}$$

where: Q_c = heat transferred due to convection

Q_r = heat transferred due to radiation

b = constant that takes into account type of combustion chamber

de = equivalent diameter of cylinder

A = heat absorbing area

t = time

ϵ = emissivity of radiating agent

σ_0 = Stefan-Boltzmann constant

The equation constitutes expressions of heat transfer due to convection, and gas and flame radiation. Explicit consideration of gas radiation and using data obtained on flame radiation measurements make this equation more complete.

Nusselt (1923) found a heat transfer coefficient formula for a spherical bomb:

$$h = 0.99\sqrt[3]{p^2T}$$

Isshiki & Nishiwaki (1974) correlated the unsteady heat transfer in a constant volume combustion chamber in an empirical manner. In their study, heat transfer measurements were made for hydrogen-oxygen-nitrogen flames for different initial pressures. Based on a rough argument on the evolution of the turbulence proposed by Hoult and Nguyen (1985), Hoult, Hamiroune and Keck (1987) found a correlation between the heat transfer from the end gas (gas ahead of the flame) to the wall and the local turbulence intensity in a turbulent combustion bomb:

$$Nu = 13.7Re_t^{1.17} = 13.7(\frac{u'R}{\nu})^{1.17}$$

where: Re_t = Turbulent Reynolds number
u' = Turbulence intensity
R = Bomb radius
ν = Kinematic viscosity

In their study, wall temperature and pressure measurements were made for three levels of initial turbulence. All tests were performed with an equivalence ratio of 1.0, so wider applications are limited.

In this study, correlations between the heat transfer to the wall before the flame strikes it and the initial turbulence intensity are developed for turbulent combustion of lean and stoichiometric mixtures. Results, together with a comparison of the present results with those of Hoult, Hamiroune and Keck (1987), are given in Chapter 4. Conclusions and recommendations for further study are presented in Chapter 5.

CHAPTER 2

THIN FILM HEAT FLUX TRANSDUCER DESIGN, THEORY AND CALIBRATION

The wall heat flux was determined from the transient wall temperature measurements made in a cubical turbulent combustion cell with a single fast response heat flux gauge. A detailed discussion of the design and calibration of the heat flux gauge as well as the theory of determination of the heat flux from the wall temperature measurements is given in this chapter.

2.1 Design of The Heat Flux Gauge

The heat flux gauge shown in Figure 2.1 consists of a thin platinum film, vacuum deposited on a ceramic substrate (Macor, Corning Glass Works). The Macor substrate is fitted into a metal housing for mounting and is held in place by epoxy on the inside of the metal housing as well as an end cap. The cap is held in place by four screws. These screws were chosen to withstand the forces produced by pressure up to 2.03 MPa [Torvi,1991]. The thin platinum film, shown in detail in Figure 2.2, is joined to copper leads by very fine gold wires which pass through the Macor base. The leads are placed in an electrical circuit (see Figure 2.3), which

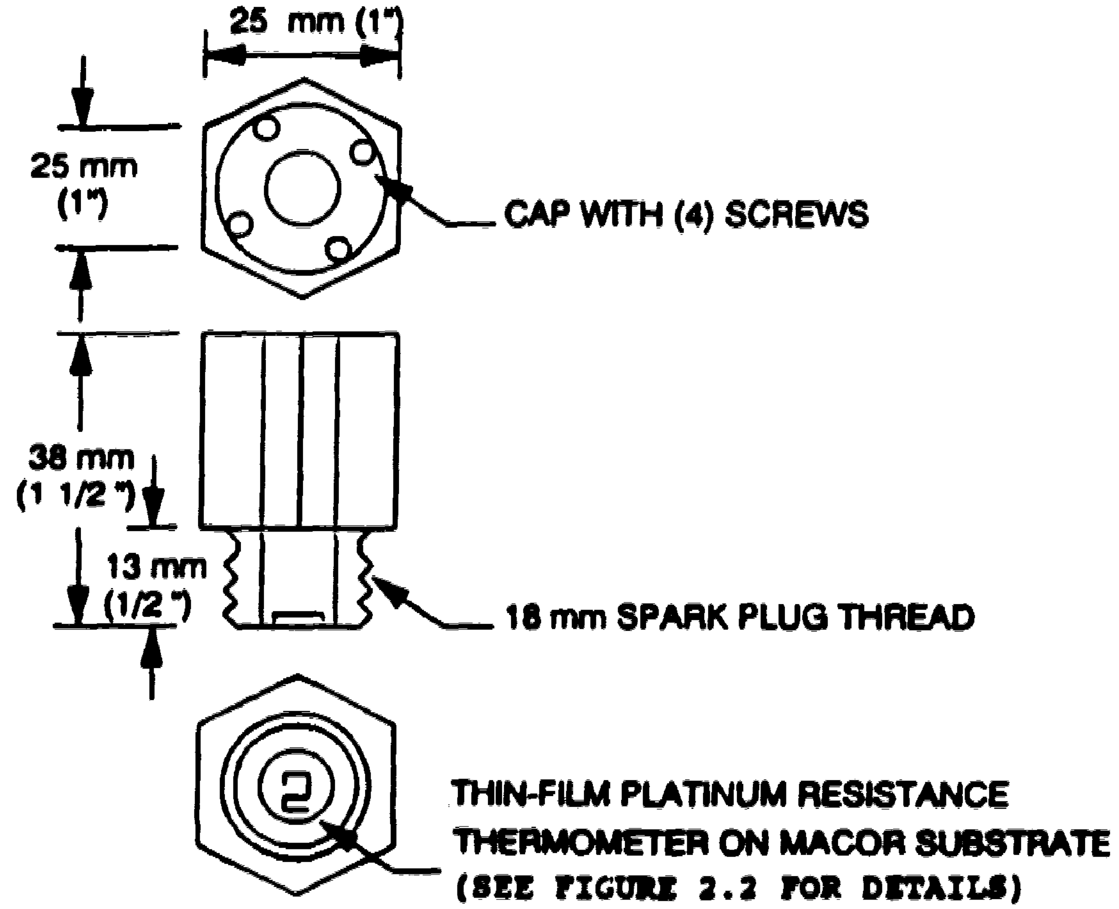

Figure 2.1 Thin film platinum resistance thermometer heat flux gauge.

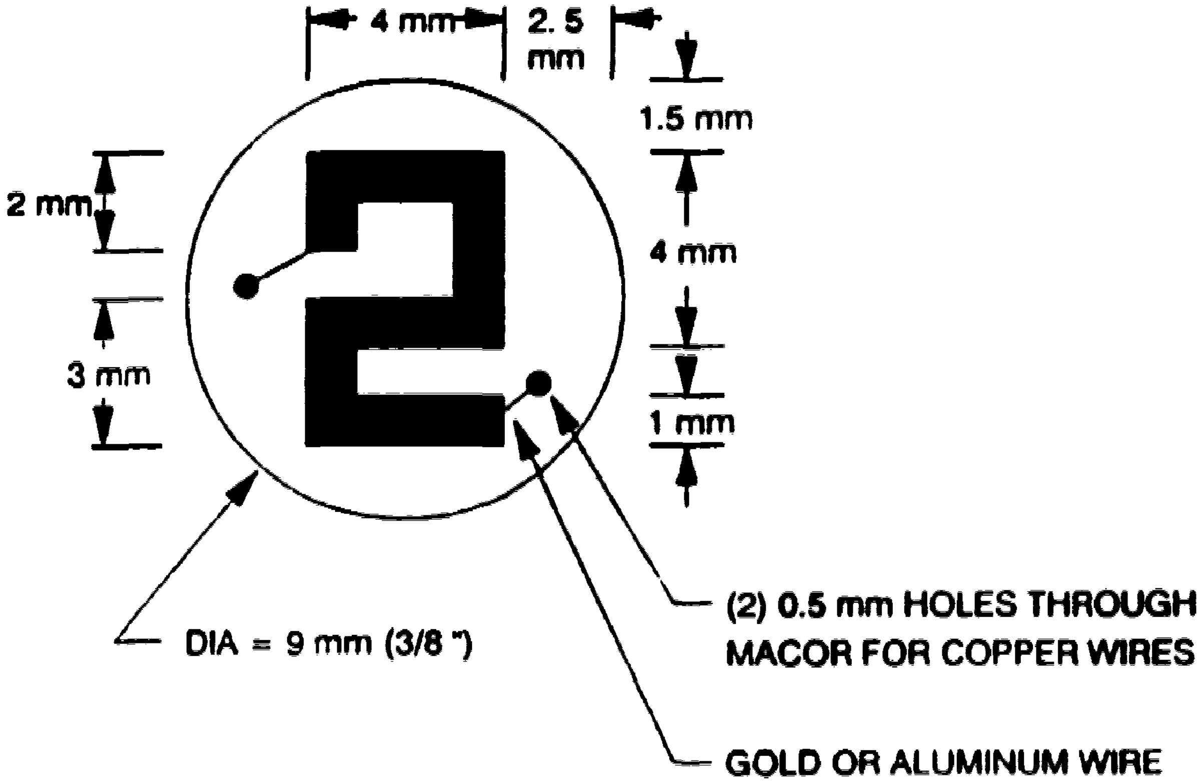

Figure 2.2 Detail of the thin film platinum resistance thermometer.

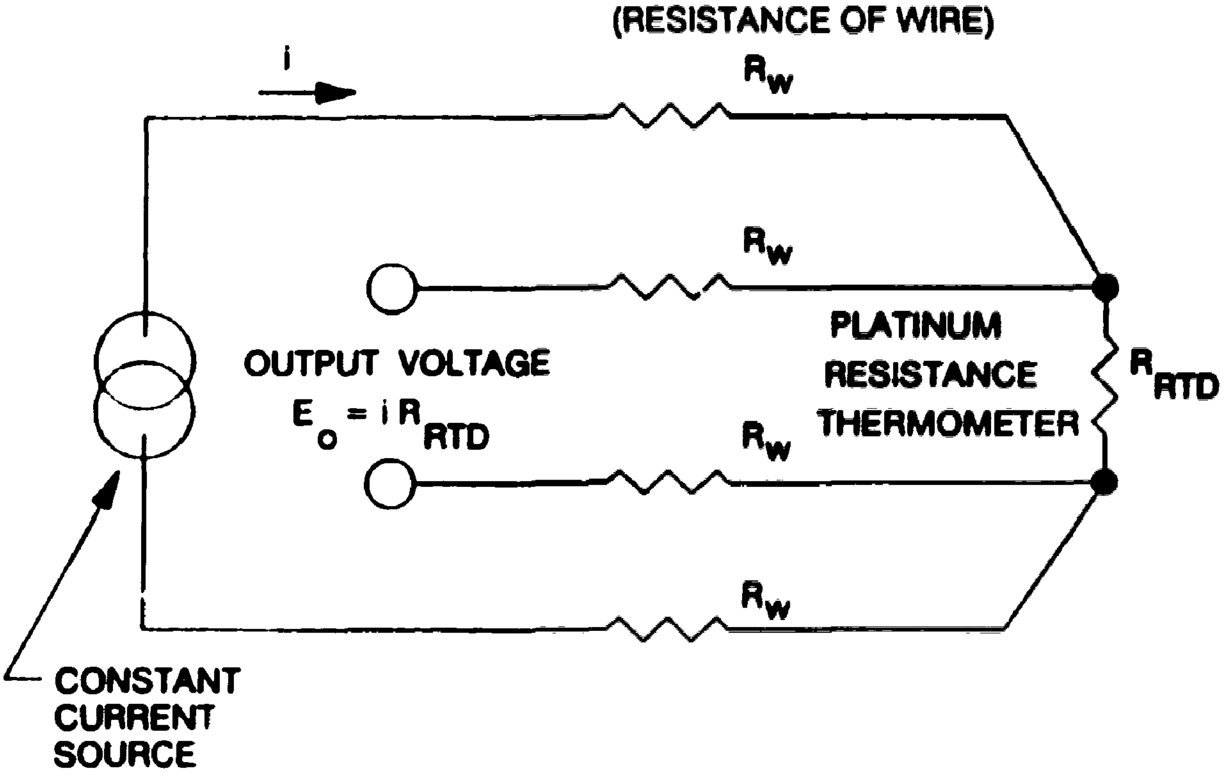

Figure 2.3 Electrical circuit for the heat flux gauge.

consists of two basic components: an amplifier for the output voltage and a constant current source. The output was recorded on a 4 channel RACAL FM tape recorder.

As shown in Figure 2.2, the thin film is of serpentine pattern, which was produced by placing a template made of stainless steel shim stock on top of the ceramic substrate during vacuum deposition of the platinum. The length of the film is about 16mm and the width is about 1mm. The resistance of the film is related to its size by the following equation.

$$\begin{aligned} R &= \frac{\rho L}{A} \\ &= \frac{\rho L}{wl} \end{aligned} \tag{2.1-1}$$

where: $\rho =$ Resistivity of platinum

$L =$ Length of the film

$A =$ Cross-sectional area of the film

$w =$ Width of the film

$l =$ Thickness of the film

The film was made as a serpentine pattern to maximize the length, and hence the thickness which affects the result of the deposition technically, for a given resistance. The thickness of the film is about 40 nm. Its resistance at room temperature is 110 ohms.

The thin platinum film was chosen because of its rapid response and high sensitivity to temperature changes. According to Hall & Hertzberg(1958), the characteristic time parameter for a thin film can be determined by the following equation

$$\tau_r = \frac{\rho_f^2 c_f^2 l^2}{\rho_b c_b k_b} \qquad (2.1\text{-}2)$$

where ρ_f, c_f are density and specific heat of the thin film, ρ_b , c_b are those of the backing material. l is the thickness of the film. For the gauge used in this study, τ_r is calculated to be about 0.01 us, which is extremely fast. The actual τ_r of the complete system was measured as discussed in section 2.3.

2.2 The Theory of Heat Flux Determination

The wall heat flux is determined from the transient wall temperature measurements. The temperature changes are measured by changes in resistance of the platinum film. The time duration of the combustion experiments in the cell is usually less than 100 ms. For these short time durations, the heat transfer into the gauge can be modelled as that into a semi-infinite plane initially at uniform temperature. The one dimensional heat conduction equation is

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \tag{2.2-1}$$

where: x = distance (direction) perpendicular to the wall

α = thermal diffusivity (= $k/\rho c$)

The initial and boundary conditions are

$$T(x,0) = T_i \tag{2.2-2a}$$

$$T(0,t) = T_w(t) \tag{2.2-2b}$$

$$T(\infty,t) = T_i \tag{2.2-2c}$$

The solution to this problem with variable wall temperature, $T_w(t)$, can be found using the solution for constant wall temperature and the Duhamel integral theorem [Carslaw and Jaeger, 1978]. The solution for constant wall temperature, T_w, is given by

$$\begin{aligned} T(x,t) - T_i &= (T_w - T_i)(1 - \frac{2}{\sqrt{\pi}} \int_0^{\frac{x}{2\sqrt{\alpha t}}} \exp(-y^2)dy) \\ &= (T_w - T_i)(1 - \mathrm{erf}(\frac{x}{2\sqrt{\alpha t}})) \equiv F(x,t) \end{aligned} \tag{2.2-3}$$

Note that when $T_w - T_i = 1$, $F(x,t)$ is the complementary error function, that is, $F(x,t) = 1 - \mathrm{erf}(\frac{x}{2\sqrt{\alpha t}}) \equiv \mathrm{erfc}(\frac{x}{2\sqrt{\alpha t}})$.

Duhamel's theorem states that if $u_1(x,t)$ is the response of a linear homogeneous system (initially at zero) to a single unit step input, the response, $u_f(x,t)$, of the system to a time varying , continuous input, $f(t)$, is given by

$$u_f(x,t) = \int_0^t f(\tau)\frac{\partial u_1(x,t-\tau)}{\partial \tau}d\tau \qquad (2.2\text{-}4)$$

Using the Duhamel integral theorem, the solution for the transient wall temperature problem can then be written as

$$T(x,t) - T_i = \int_0^t (T_w(\tau) - T_i)\frac{\partial}{\partial t}F(x,t-\tau)d\tau$$

or

$$\begin{aligned} T(x,t) - T_i &= (T_w(0) - T_i)(1 - \mathrm{erf}(\frac{x}{2\sqrt{\alpha t}})) \\ &\quad + \int_0^t (1 - \mathrm{erf}(\frac{x}{2\sqrt{\alpha(t-\tau)}}))\frac{dT_w(\tau)}{d\tau}d\tau \end{aligned} \qquad (2.2\text{-}5)$$

Therefore, the wall heat flux given by

$$\begin{aligned} q_w &= -k\frac{\partial T}{\partial x}|_{x=0} \\ &= \sqrt{\frac{k\rho c}{\pi}}\int_0^t \frac{1}{\sqrt{t-\tau}}\frac{dT_w(\tau)}{d\tau}d\tau \end{aligned} \qquad (2.2\text{-}6)$$

By integrating by parts, the following convenient result for numerical calculation is obtained:

$$q_w(t) = \sqrt{\frac{k\rho c}{\pi}}\left[\frac{T_w(t) - T_i}{\sqrt{t}} + \frac{1}{2}\int_0^t \frac{T_w(t) - T_w(\tau)}{(t-\tau)^{3/2}}d\tau\right] \qquad (2.2\text{-}7)$$

The bulk value for thermal absorptivity, $\sqrt{k\rho c}$, of Macor is 1395 $W.s^{1/2}.m^{-2}.K^{-1}$ [Woodard, 1982]. The actual value was determined by calibration as described in section 2.3. The thermal absorptivity is approximately constant for the temperature range considered. As shown in equation (2.2-7), the wall heat flux depends only on the wall temperature variation and the thermal absorptivity. Once the thermal absorptivity and experimental measurements of wall temperature variations are obtained, a numerical calculation of the wall heat flux can be made with equation (2.2-7) [Dale, et al.,1992 and Leung, 1991]. The equation (2.2-7) was numerically integrated using the Trapezoidal rule in this study. The computer program used for heat flux calculation is given in Appendix A (part 2).

2.3 Calibration

To calculate the wall heat flux, the exact value of the thermal absorptivity of the Macor substrate is needed. The calibration procedure consists of three steps.

The primary step was the determination of the temperature coefficient of resistance of the thin platinum film. The temperature coefficient of resistance was calibrated quasi-steadily in a calibration bath(Model 910AC, Rosemount Engineering Company). It was done by wrapping the gauge with thin plastic film before putting it into the liquid tank. The leads from the thin film were connected with an ohm meter which gave a measure of the resistance while a thermometer immersed in the liquid tank gave a temperature reading. The result, as shown in Figure 2.4, is 0.19 ohms/°C.

The second step was the determination of the output of the electrical circuit as a function of the temperature change of the ceramic surface. Again, the sensor-amplifier combination was calibrated using the aforementioned calibration bath. This time, the leads from the gauge were connected with a specially built bridge amplifier called the RTD (Resistance Temperature Detector) signal conditioner, the detailed schematic of which is presented in Figure 2.5. The temperature reading of the ceramic surface of the heat flux gauge (i.e. RTD) was then compared to the bridge amplifier output. The result is shown in Figure 2.6. A calibration constant, in degrees Celsius per Volt output, was thus obtained for this gauge and amplifier circuit. For this system it is 9.64 mV/°C

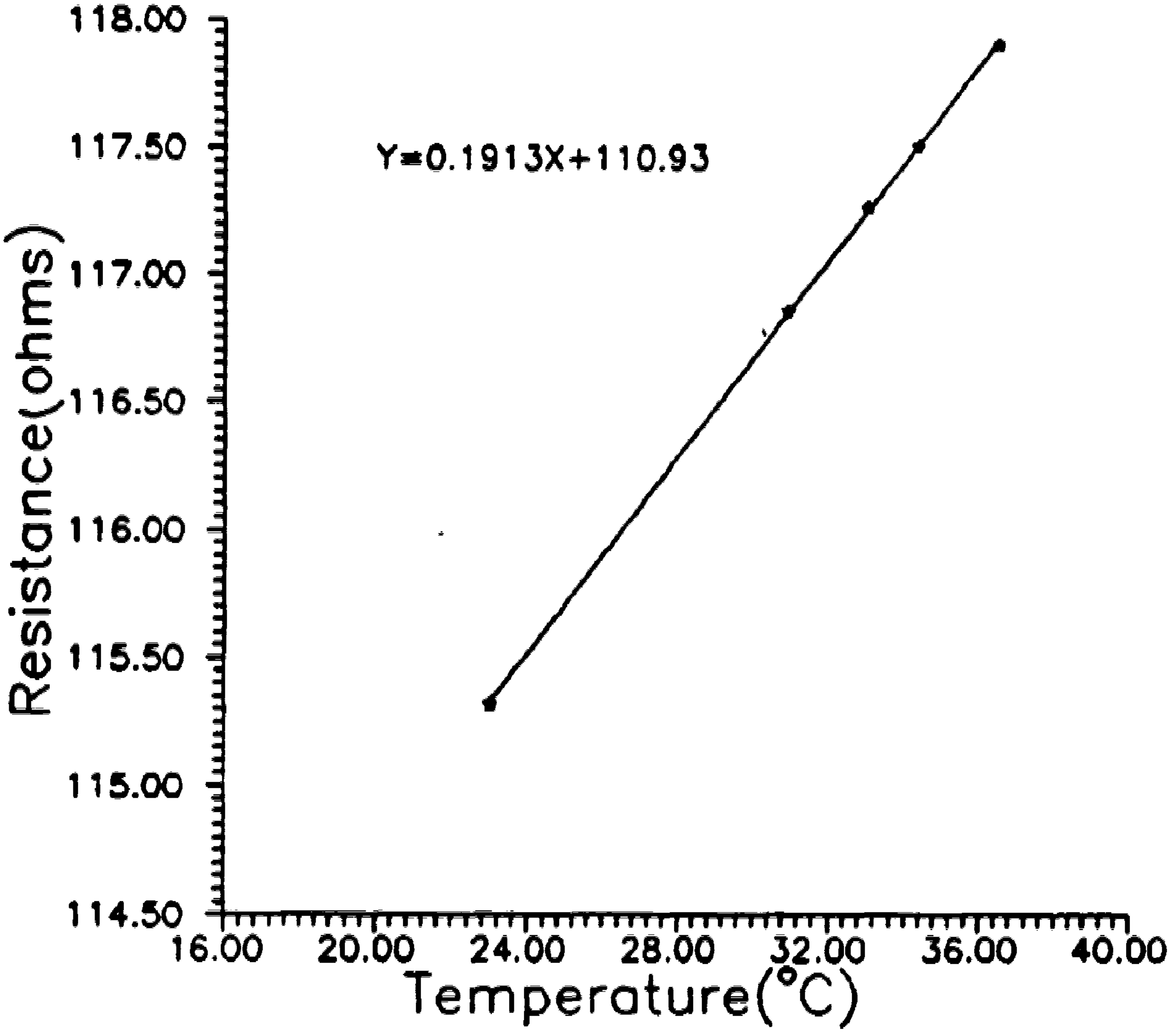

Figure 2.4 Temperature coefficient of resistance of the thin platinum film.

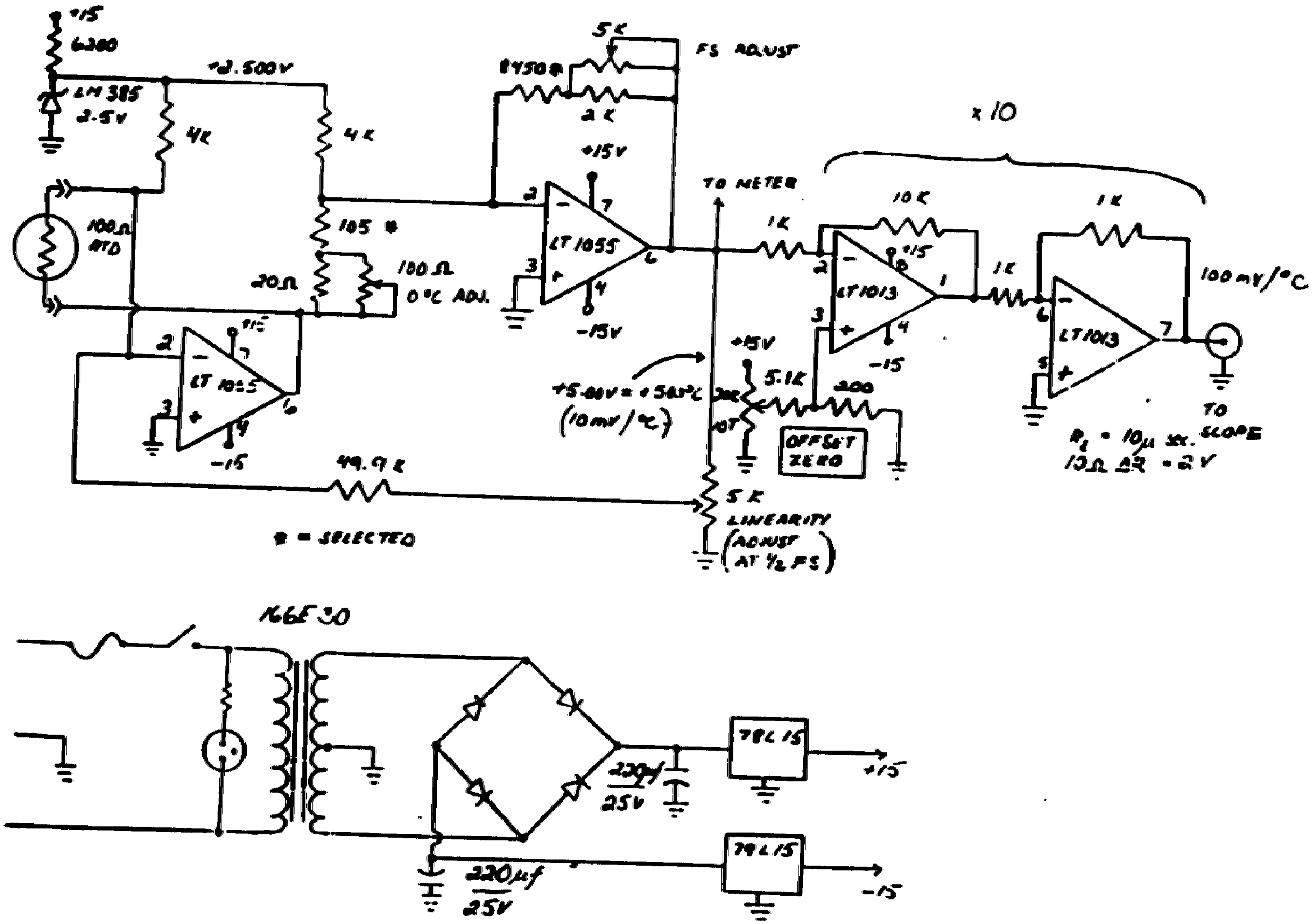

Figure 2.5 Schematic of RTD heat flux gauge signal conditioner.

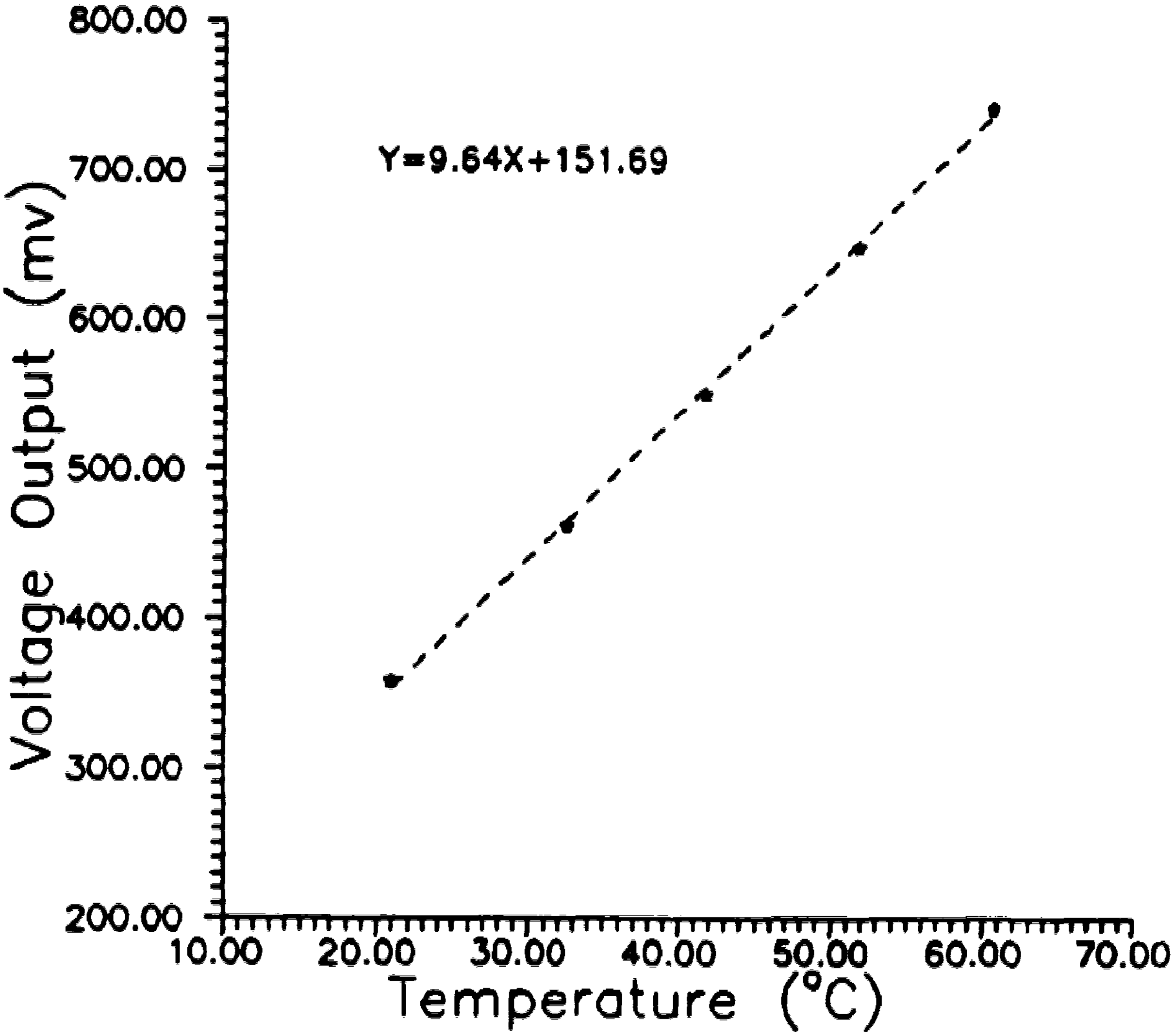

Figure 2.6 RTD heat flux gauge signal conditioner output calibration.

or 103.7 °C/V.

The final stage was to calibrate the thermal properties of the substrate. It can be shown (Carslaw and Jaeger, 1959) that for a semi-infinite solid, such as the Macor substrate, with constant initial temperature and thermal physical properties subjected to a constant heat flux on its surface, that the temperature rise at any point in time and space is given by

$$T(x,t) - T_i = \frac{2q_0\sqrt{\alpha t/\pi}}{k}\exp\left(-\frac{x^2}{4\alpha t}\right) - \frac{q_0 x}{k}\mathrm{erfc}\left(\frac{x}{2\sqrt{\alpha t}}\right) \qquad (2.3\text{-}1)$$

where q_0 is the constant heat flux (W/m^2), t is the time elapsed(s), and x is the depth into the solid(m).

For the surface of the Macor substrate, (i.e. $x = 0$), Equation (2.3-1) reduces to

$$\Delta T = T(x,t) - T_i = \frac{2q_0\sqrt{\alpha t/\pi}}{k} = \frac{2q_0\sqrt{t}}{\sqrt{k\rho c\pi}} \qquad (2.3\text{-}2)$$

Equation (2.3-2) was used for determination of the actual value of the thermal absorptivity of the Macor substrate. It was done by exposing the ceramic surface of the heat flux gauge to a known constant radiant heat flux. The heat flux was produced by using a projector bulb for a very short period of time (about 500ms) and measuring the surface temperature rise ΔT versus time t. The result was recorded on a Hewlett-Packard 7100B strip chart recorder (see Figure 2.7), from which five points were picked and applied into Equation (2.3-2). As shown in Figure 2.8, the value of $\frac{2q_0}{\sqrt{k\rho c\pi}}$ in Equation (2.3-2) was found to be 8.79. The constant heat flux generated by the projector bulb at 100V was checked with three specially made copper slug calorimeters and was found to be 11084 W/m^2. The value of the thermal absorptivity $\sqrt{k\rho c}$ was found to be 1423 $W.s^{1/2}.m^{-2}.K^{-1}$, which is in good agreement with the bulk value which Woodard (1982) used in her study.

To check the characteristic time of the thin film gauge, a shock tube (Figure 2.9) was used. The gauge was placed at one end of the shock tube (see Figure 2.9). When the shock tube drive persaure, P_1, is greater than 1.55 times the measurement section pressure, P_2, a shock wave will occur when the separating diaphragm is broken. The shock speed was measured using shock wave detectors. The shock wave was at a speed close to M = 1.0. The response of the heat flux gauge after a shock wave hits is presented in Figure 2.10, from which, a response time of 2 us was found for the gauge - amplifier system. This result is much longer than the 0.01us characteristic time estimated for the thin platinum film alone from Equation 2.1-2. It could be that the electronic amplifier is not fast enough to detect the true response time of the thin platinum film gauge. However, a 2μs response time is adequate for an experiment with characteristic time scales measured in ms.

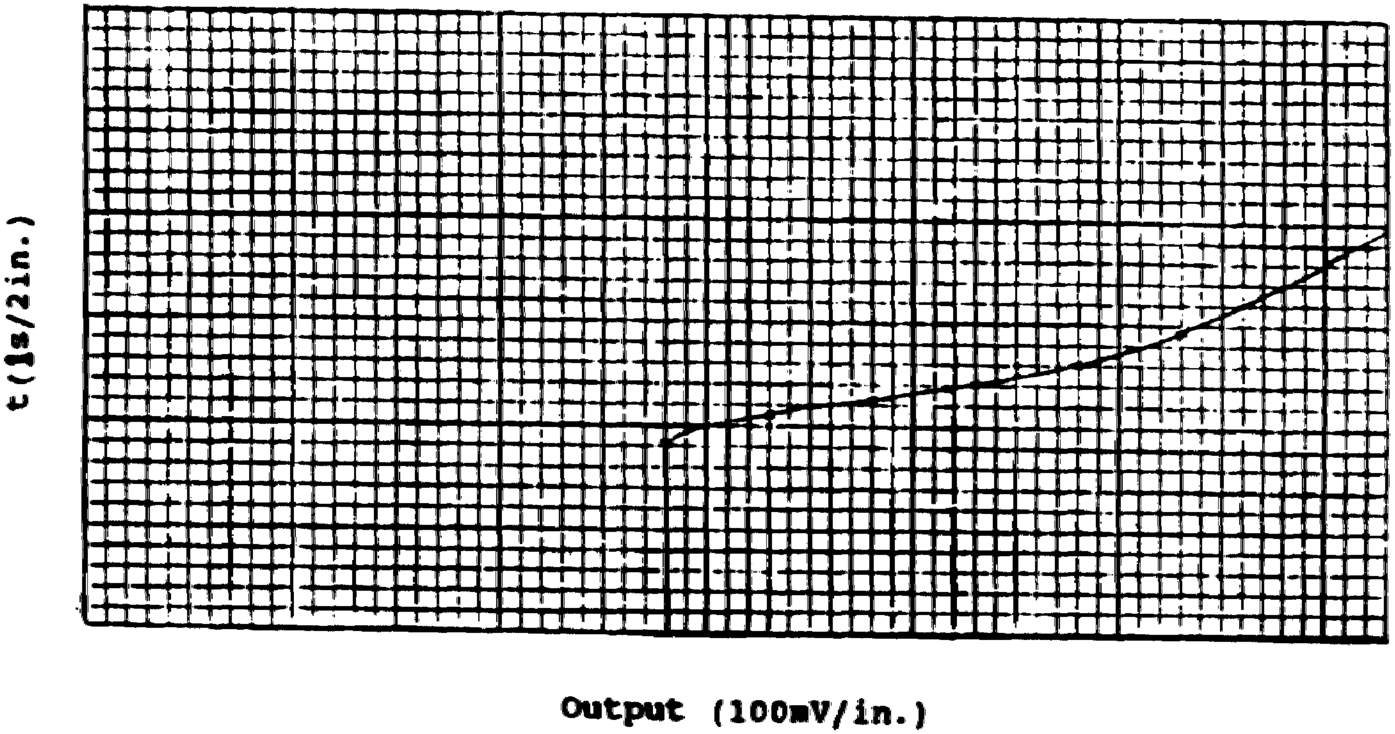

Figure 2.7 Recorded response of the heat flux gauge to a constant heat flux on its surface.

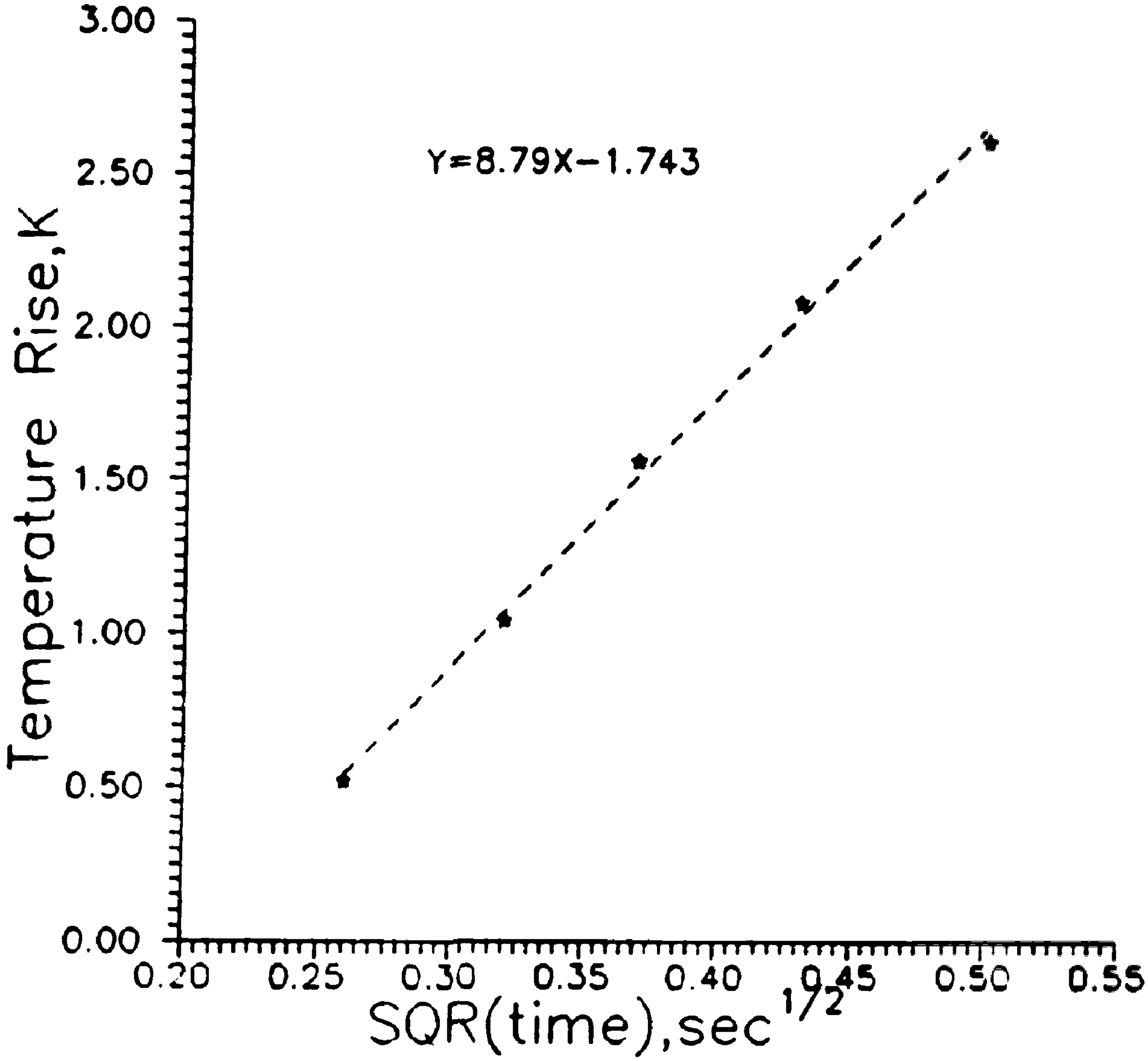

Figure 2.8 Calibration to measure the absorptivity of Macor, using a constant heat flux.

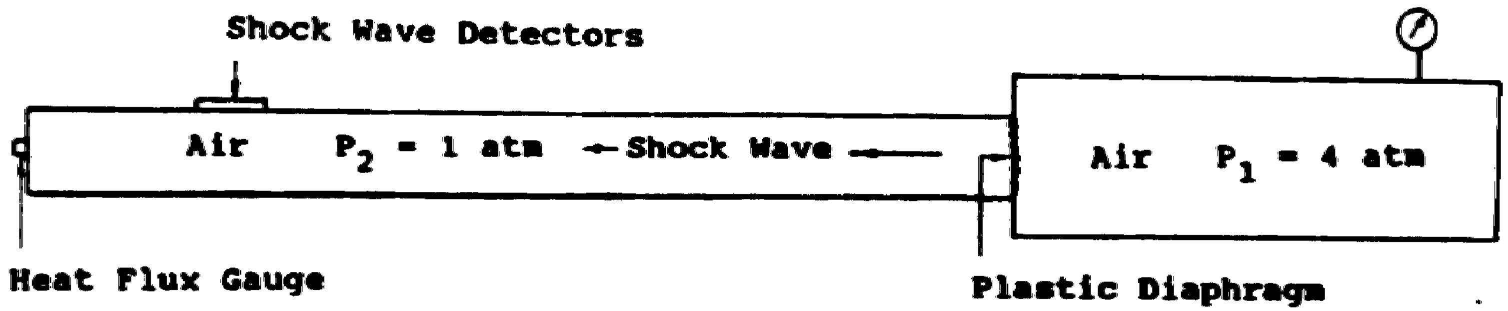

Figure 2.9 Schematic of the shock tube.

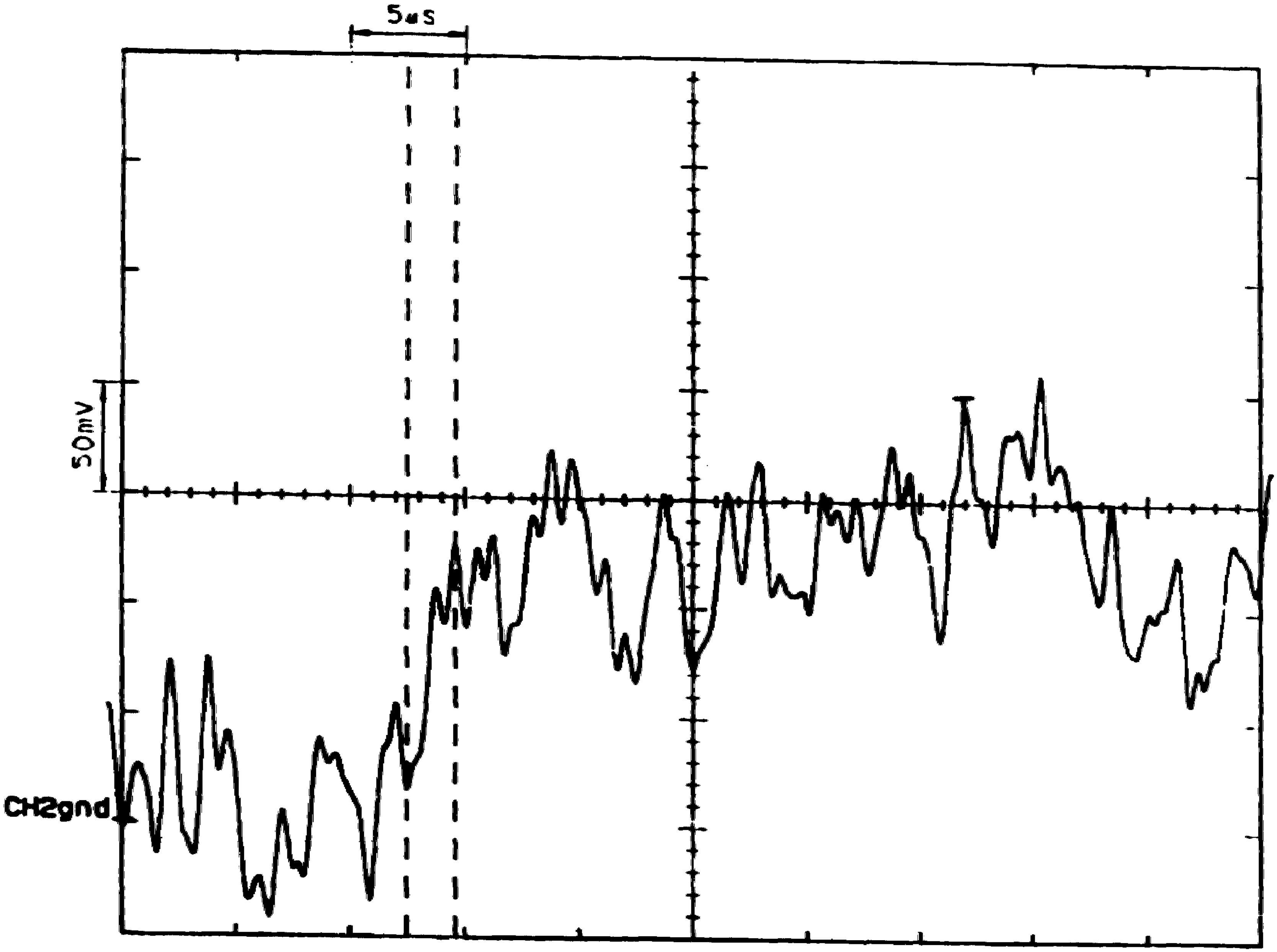

Figure 2.10 The response of the heat flux gauge to a shock wave (M = 1.0), amplifier gain 1900/1.

CHAPTER 3

EXPERIMENTAL SYSTEM AND PROCEDURE

3.1 Apparatus

3.1.1 Turbulent Combustion Chamber and Instrumentation

The experiments were performed in a constant volume turbulent combustion chamber. The chamber used here was based on the original design by Checkel and Thomas [Checkel, 1981; Checkel and Thomas, 1983]. The details of this chamber are described by McDonell (1988), Modien (1990), and Ting (1992). The 125mm cubic chamber, shown in Figure 3.1, is made of 6066-T6 aluminum alloy which is machined and polished. All walls of the chamber are 25mm thick. Two circular PK-7 optical glass windows are mounted on the opposing side (front and back) of the chamber. These windows are 30mm thick. The cell is equipped with platinum tipped central spark electrodes, one of which is mounted on a micrometer head for spark gap adjustment. The spark electrodes pass through the centre of the chamber. A spark gap of 5.00mm was used throughout this study.

Turbulence in the cell was generated by quickly moving a perforated plate across the cell. The plate finishing position is shown in Figure 3.1. A variety of perforated plates are

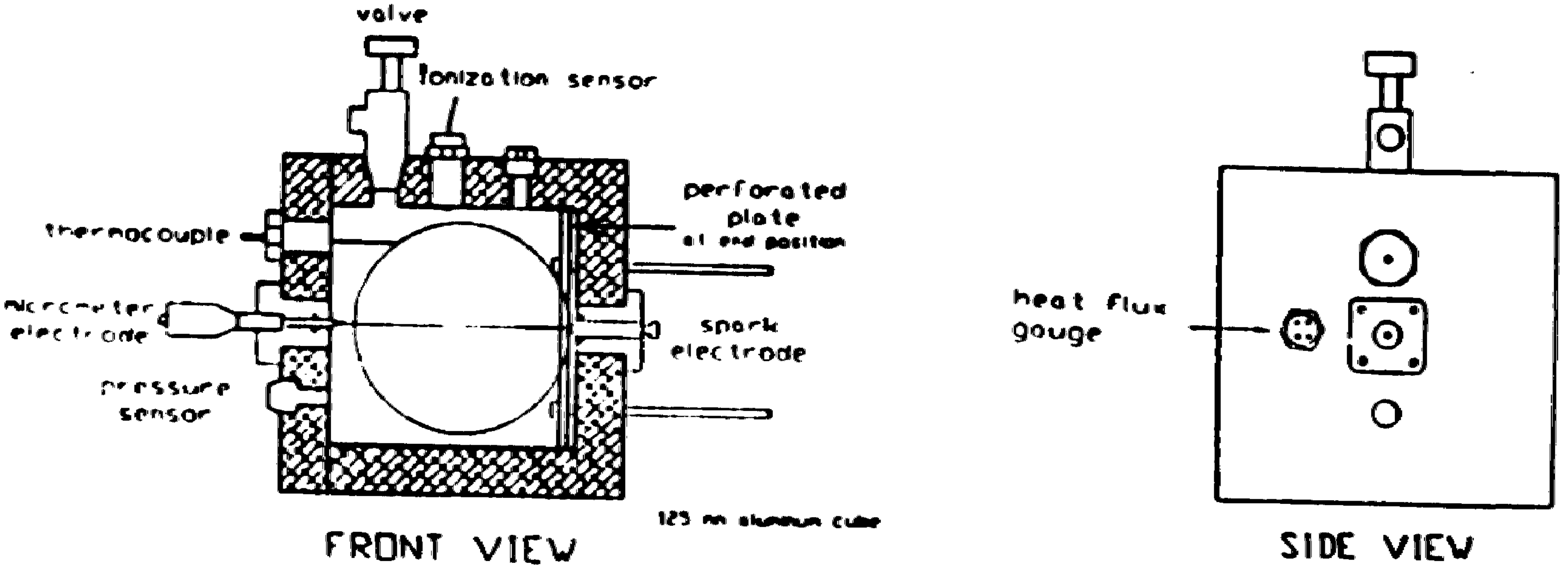

Figure 3.1 The cubical turbulent combustion cell.

available to produce turbulence in the cell. They have holes of diameter D, ranging from 5mm to 20mm, placed on alternate intersections of a grid with spacing D to ensure that each plate has 60% solid area. The plate used in this study was the 10 mm diameter plate. A similar 20mm perforated plate is shown in Figure 3.2. Details of the plate movement mechanism are given by McDonell(1988) and Modien (1990). Figure 3.3 shows the entire plate movement mechanism.

The combustion cell was instrumented with a pressure transducer, a heat flux gauge and one flame ionisation probe (see Figure 3.1). Three measurements were made during an experimental run: the chamber pressure, the wall heat flux at one point, and the ionization probe output signal. A schematic of the experimental setup is shown in Figure 3.4.

The pressure transducer used in this study was a Norwood model III four-active-arm strain gauge type with a response frequency of 45KHz. The pressure gauge amplifier had variable off set and multiple amplification factors of 100, 300, 500, 800 and 1000. The amplification factor was set at 500 in this study. The pressure transducer was located on the wall of the combustion cell as shown in Figure 3.1. The amplified output of the pressure transducer was recorded on an 4 Channel RACAL FM Tape Recorder. The pressure transducer and amplifier were

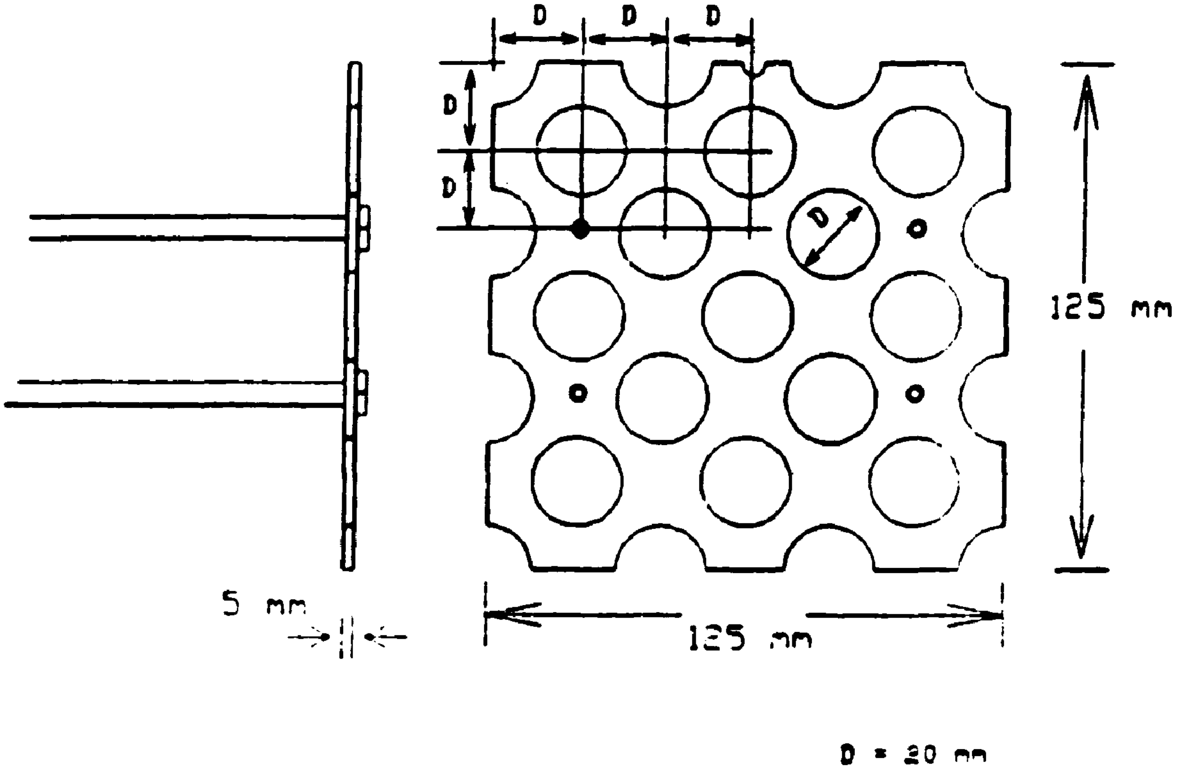

Figure 3.2 The 20 mm diameter perforated plate.

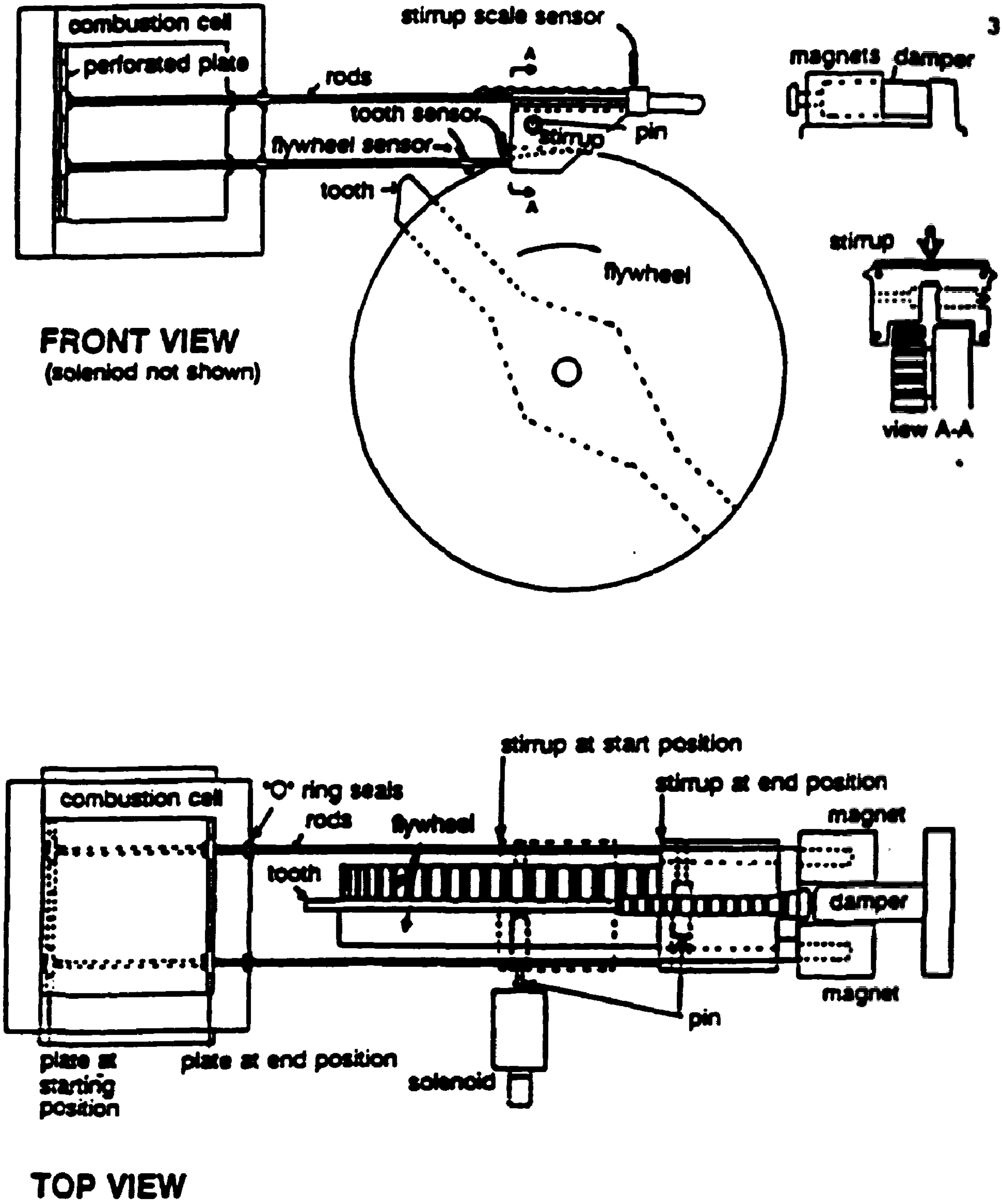

Figure 3.3 The perforated plate movement mechanism.

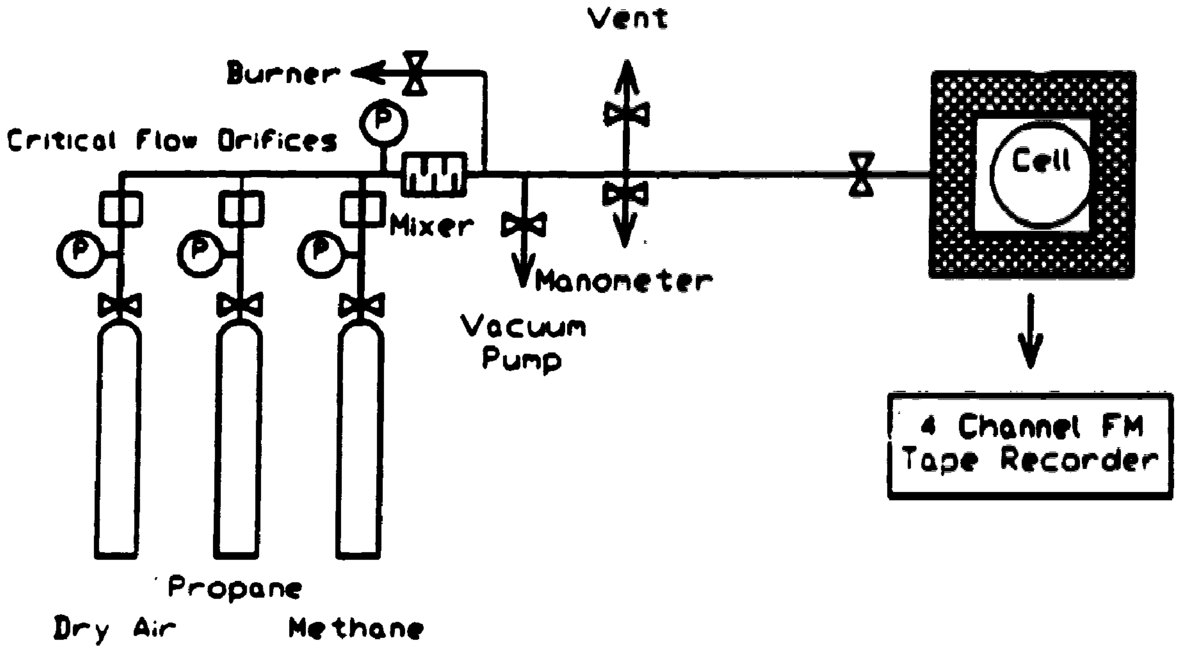

Figure 3.4 Schematic of the experimental setup.

calibrated periodically on a dead weight tester.

The thin film platinum resistance thermometer was used to measure the transient wall temperature. Details of the design and calibration of the heat flux gauge, and the determination of the heat flux from the wall temperature measurements have been presented in Chapter 2.

An ionisation probe was used to detect the arrival of the flame front. As shown in Figure 3.5, a constant d.c. voltage potential of 50 V was held across the exposed tips of 22 ga. platinum wire which were separated by 0.1 to 0.5 mm. When the flame front reaches the gap between the wire tips, current flows between the tips carried by the ions in the flame front. Then the current amplifier produces a spike in the ionisation probe output signal. The probe was located in the center of the top wall of the cell (tips are 60mm from the spark gap, 2.5mm from the top wall) as shown in Figure 3.1.

3.1.2 Gas Metering and Mixer System

The oxidizer (air) and fuel (99.9% pure methane) were obtained from high pressure bottles. Each gas passed through critical flow orifices before being mixed. With known flow rates of both the oxidizer and the fuel, the two gases passed through a mixer to produce a homogenous mixture of known

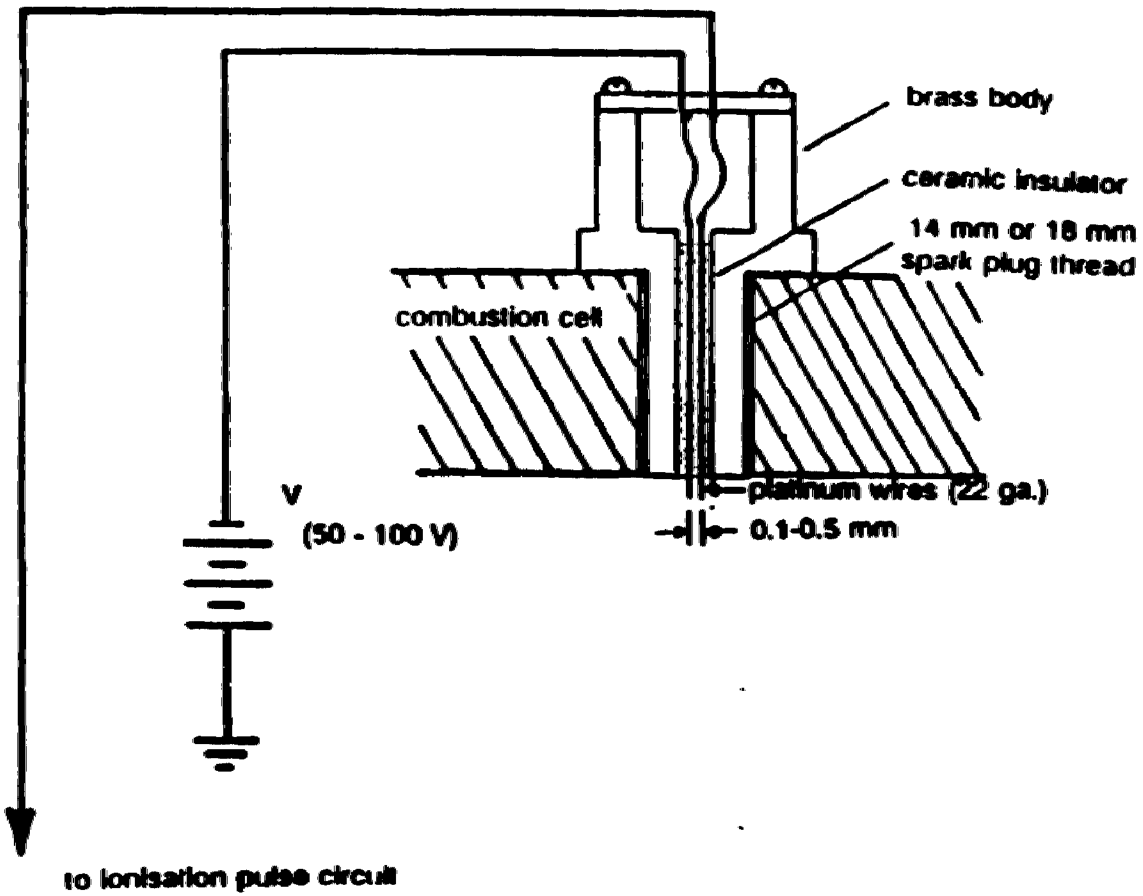

Figure 3.5 A typical ionisation probe.

equivalence ratio. As shown in Figure 3.6, the critical flow orifice gas metering and mixer system consists of pressure gauges, critical flow orifices, and a mixer.

The pressure gauges measure the upstream and downstream pressures of the orifices. The upstream pressure from the gas cylinder is regulated using a pressure regulator, while the downstream pressure is that of the atmosphere or that of the combustion chamber. For constant upstream temperature, the volumetric flow rate through a critical flow orifice is a function of only the upstream pressure. For critical flow, the upstream pressure has to satisfy the following condition:

$$\frac{p_u}{p_d} \geq \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma - 1}} \tag{3.1-1}$$

where: $p_u =$ upstream pressure

$p_d =$ downstream (ambient) pressure

$\gamma =$ specific heat ratio

Table 3.1 lists the minimum upstream pressures for a downstream pressures of 1 atm in order to have choked flow in the orifices. For convenience, methane gas pressure was held constant at 220kPa for a downstream pressure of 1 atm while air pressure was varied to obtain the required equivalence ratios. The upstream air flow rate was calibrated using a

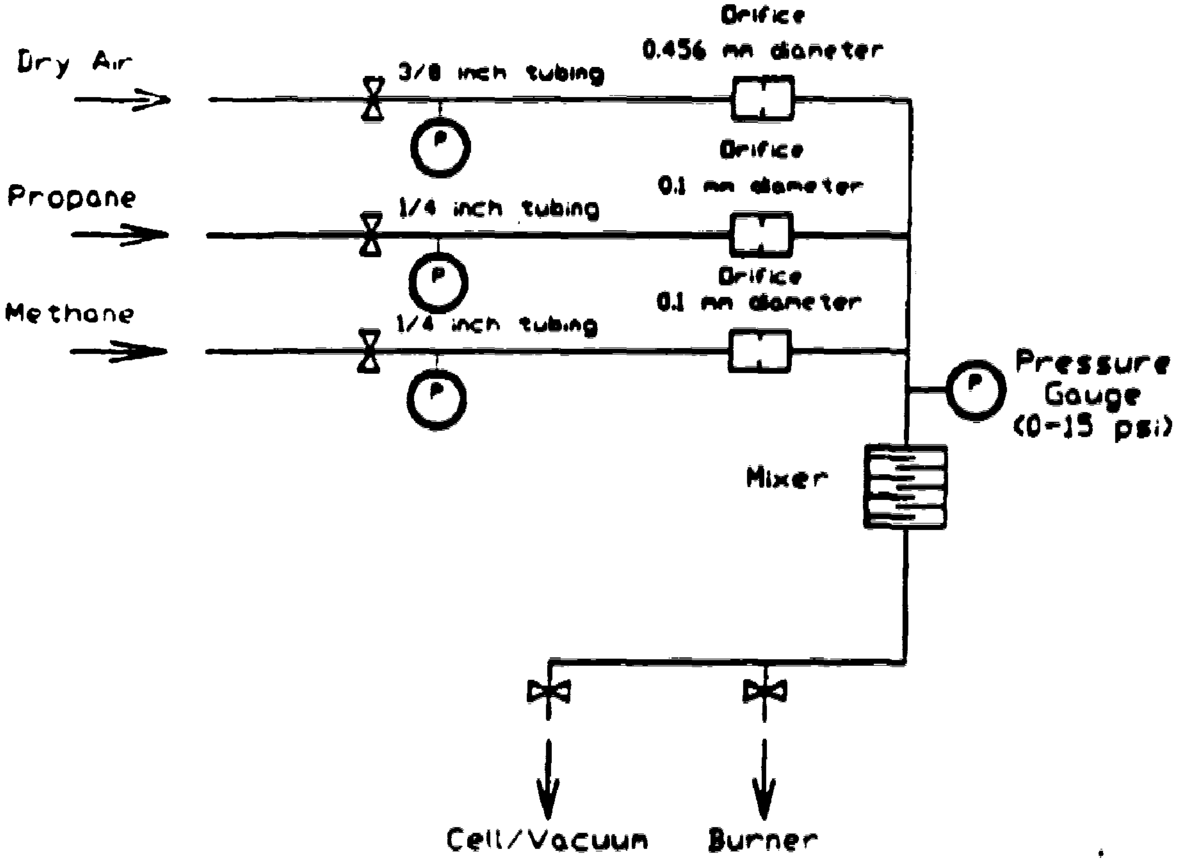

Figure 3.6 Schematic of the critical flow orifice gas metering and mixer system.

rotameter. The methane flow rate was calibrated by the soap bubble method. The original calibration of the choked orifice flow was done by McDonell (1988). The detailed re-calibration of air and methane flow rate was given by Ting (1992).

Table 3.1 Minimum upstream pressures for critical flow

Gas	p_u (for p_d = 1 atm)
Air	1.893 atm
Methane	1.832 atm

3.1.3 Ignition

An ignition system can play an important role in early flame development, the burning duration and the burning velocity of a mixture. The ignition system used in this study was the high energy capacitance discharge unit which was also used by McDonell (1988), Modien (1990), and Ting (1992). Ignition of the unburnt gases was accomplished by means of a discharge across a 5mm spark gap using 312mJ of stored energy. A schematic of the ignition system circuit is shown in Figure 3.7.

A high voltage DC supply unit, capable of supplying up to 2000 V, was used to supply the required voltage. This voltage charges the capacitor bank of variable capacitance (1, 1.5, 2, and 2.5 uF). When the SCR is activated by the electric

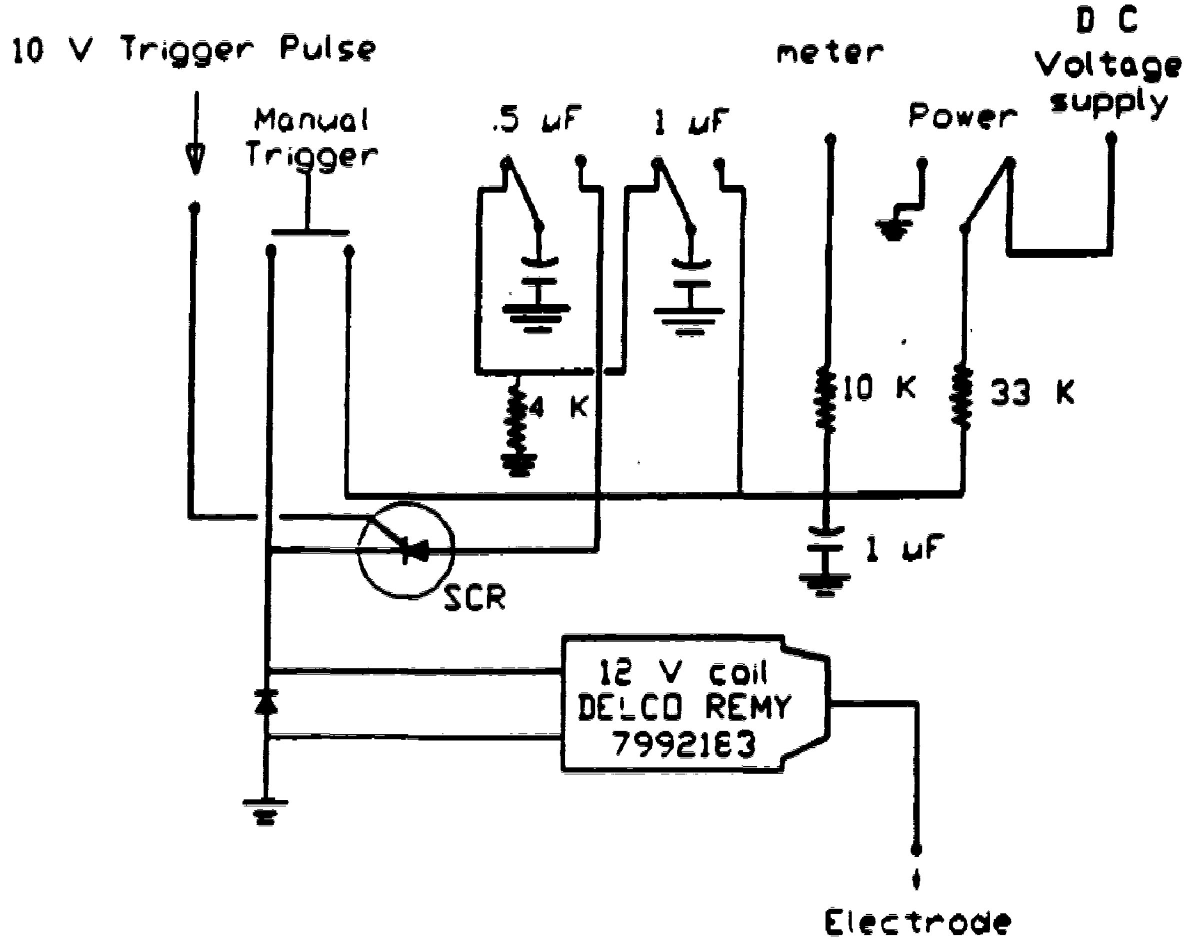

Figure 3.7 Schematic of the high energy capacitance discharge ignition circuit.

trigger, the current discharges through the primary windings of a standard automotive coil to produce the spark. The 2.5uF of capacitance was charged to 500V in this study.

3.2 Procedure

3.2.1 Quiescent Flame Tests

For laminar burning tests, equivalence ratios of 0.6, 0.75, 0.85, 1.0 were studied, using three different initial pressures (0.5, 1.0, 1.5 atm). Four or five runs were repeated for every single test condition. Between runs, the combustion chamber was evacuated and flushed with air once, and then with the supply gas mixture twice to ensure that the dead volume left in the manifold or the combustion chamber had the same composition as the supply gas.

3.2.2 Turbulence Measurements and Turbulent Combustion Tests

Pre-ignition turbulence in the cell was generated by quickly moving a perforated plate across the cell. The turbulence characteristics produced by perforated plates have been documented previously by Checkel (1986) and Mcdonell (1988). They used conventional hot wire anemometry to measure the decaying turbulence behind the perforated plates.

Measurements were performed downstream of similar, stationary perforated plates in a small wind tunnel. Limited similar measurements in the combustion cell were done and compared with those in the wind tunnel. The results are comparable according to them [Checkel, 1986; Mcdonell, 1988].

A simple turbulence decay model is expressed as

$$\frac{\sqrt{\bar{u}^2}}{U} = c_1\left(\frac{X}{D}\right)^{c_2} \qquad (3.2\text{-}1)$$

where: $\sqrt{\bar{u}^2}$ = RMS intensity (= u')

X = distance downstream of the plate

D = hole diameter

U = mean component of velocity

and

$$\frac{\Lambda}{D} = c_3\left(\frac{X}{D}\right)^{c_4} \qquad (3.2\text{-}2)$$

where: Λ = turbulence integral length scale

Decay/Growth coefficients and exponents c_1, c_2, c_3 and c_4 are listed in Table 3.2 and Table 3.3. The turbulence within the cell is homogeneous after a time, t = X/U, following the plate passage such that X/D > 10. Only X/D values great than 10 were used. Otherwise the jetting action of the airflow through the holes may result in inhomogeneous turbulence. Here, a turbulence integral length scale was about 4mm. The perforated plate speed was the mean component of velocity, U, and delay time before ignition was determined by X/U. The turbulence scale and intensity were set for the time of spark discharge.

Table 3.2 RMS intensity decay constants

Region	c_1	c_2
$X/D < 10$	10.96	-1.812
$10 < X/D < 20$	2.627	-1.191
$20 < X/D < 40$	0.773	-0.783

Table 3.3 Integral scale growth constants

Region	c_3	c_4
$X/D < 14.3$	0.38	0
$X/D > 14.3$	0.1	0.5

For turbulent burning tests, an initial pressure of only 1.0 atmosphere was used, while the equivalence ratio was set at either 0.6, 0.75, 0.85 or 1.0. The perforated plate with 10mm diameter holes was used throughout this study. Turbulence intensity at the time of spark ignition varied from 0.5 m/s to 3.0 m/s. This was controlled by setting different speeds of speeds of the flywheel which moves the plate (see Figure 3.3) and different time delays before ignition. The actual plate speed and time delay before ignition were recorded in conjunction with the pressure trace. As with the quiescent flame tests, a calibration of the pressure transducer was done prior to each series of tests. Each test condition was repeated four to five times. The combustion chamber was evacuated and flushed with the air once and the supply gas mixture twice between two consecutive runs.

3.3 Data Acquisition

A 4 channel RACAL FM tape recorder was used to record all experimental data. The data were then digitized using a Metrabyte DASH16 board for storage and analysis on an IBM compatible 486 computer. The input range on each of the four channels was selected to provide a maximum signal-to-noise ratio and the best measurement resolution for the signal being recorded.

3.3.1 Quiescent Runs

The path of data collection for quiescent runs is shown in Figure 3.8. The four channels used in quiescent tests are

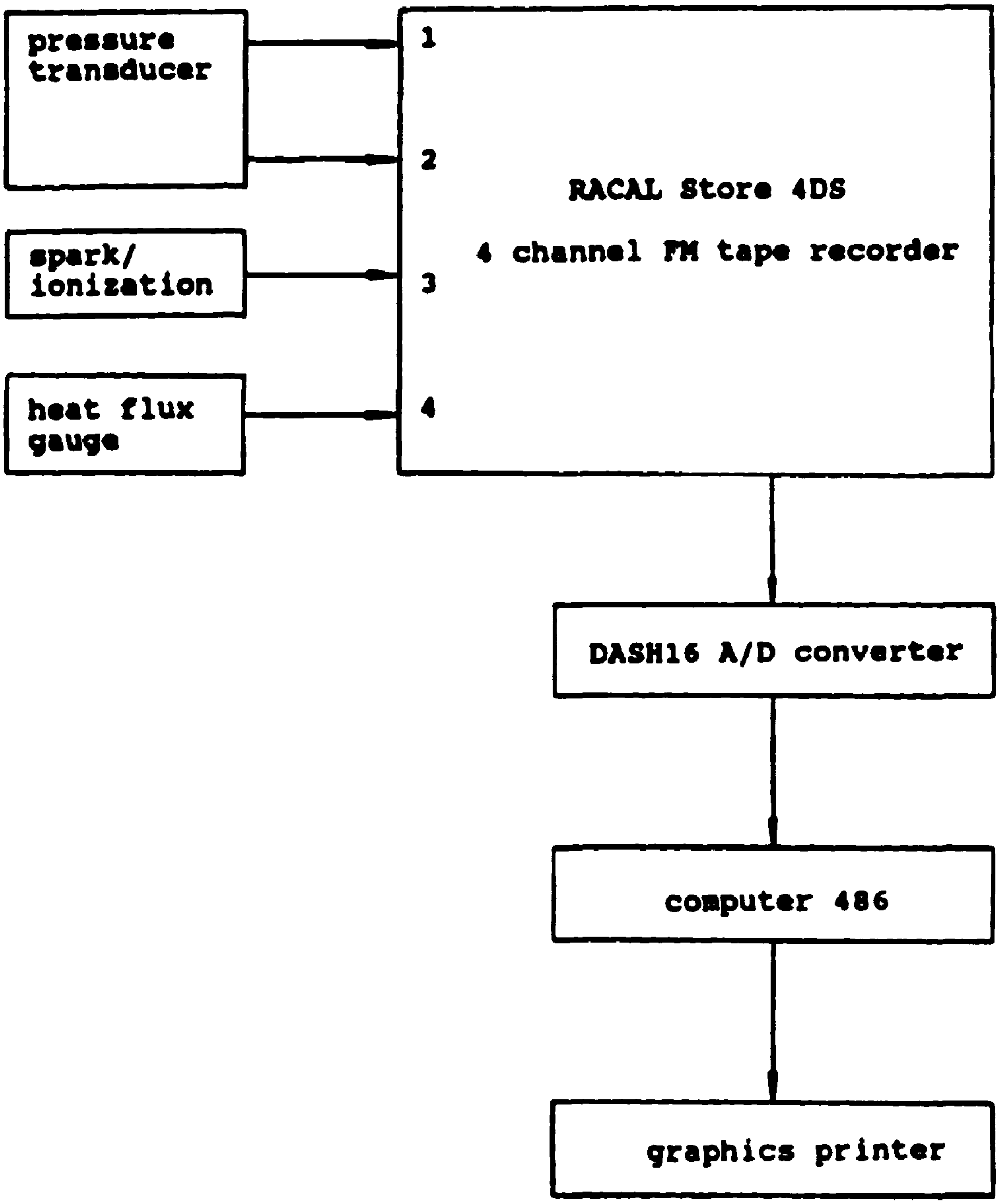

Figure 3.8 Schematic of the data acquisition system for quiescent runs.

listed in Table 3.4. Using a Metrabyte DASH16 board and a 486 computer, the signals recorded on the FM tape were digitized at a frequency of 4kHz, 4kHz, 3kHz, 1kHz respectively for burning mixtures of equivalence ratio 1.0, 0.85, 0.75, and 0.6.

The method of determination of the heat flux from the recorded wall temperature variations was given in Chapter 2. The analysis used for predicting the temperature of the compressed unburnt mixtures from the pressure trace was the multi-zone model which presumes adiabatic compression of an ideal gas mixture as described in Modien (1990) and Ting (1992).

Table 3.4 FM tape recorder channel inputs for quiescent runs.

channel	range(v) unipolar	function
1	0 to 4	high resolution pressure
2	0 to 10	maximum pressure
3	0 to 10	spark / ionization
4	0 to 1	heat flux

3.3.2 Turbulent Runs

Figure 3.9 shows the path of data collection for the turbulent runs. The actual plate motion was recorded. As shown in Figure 3.3, the plate was attached to a stirrup marked with

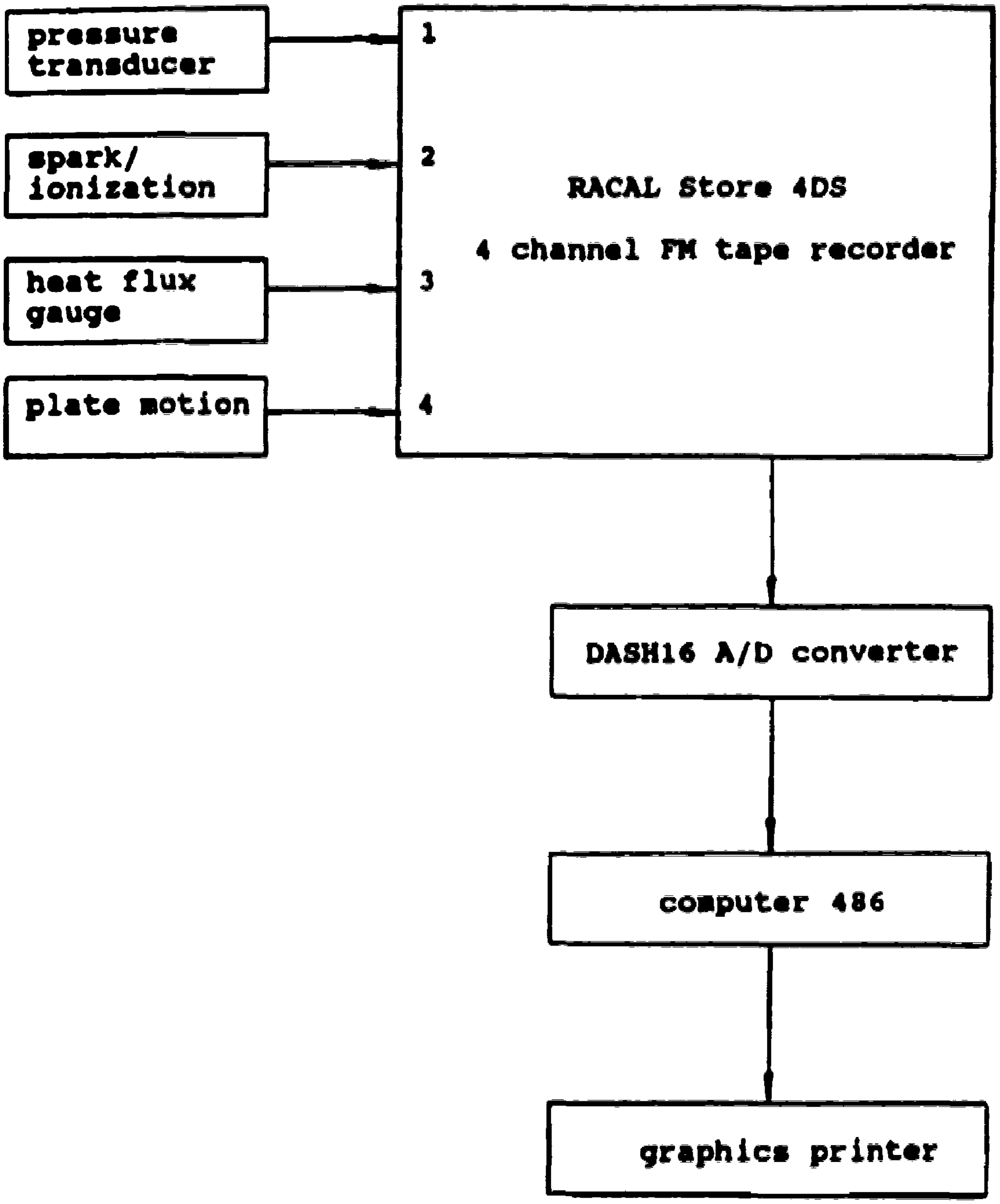

Figure 3.9 Schematic of the data acquisition system for turbulent runs.

black and white striped scales. Optical sensors were used to monitor the plate speed by focusing on the alternating black and white markers. Table 3.5 lists the function of the four channels on the FM tape recorder. The stored analog data from the FM tape were then digitized using a DASH16 board with a 486 computer at 4kHz. The turbulence intensities at the time of spark discharge can be calculated from the actual plate speed and the actual spark delay time measured from the FM tape record. More variables were involved in turbulent combustion tests. In order to prevent the inclusion of any wild data due to noise, runs where the actual plate speed was more than ± 5% from the required average were not used. This resulted in using two to five runs for averaging any data point.

Table 3.5 FM tape recorder channel inputs for turbulent runs.

channel	range(v) unipolar	function
1	0 to 10	pressure
2	0 to 10	spark / ionization
3	0 to 1	heat flux
4	0 to 10	plate motion

CHAPTER 4

EXPERIMENTAL MEASUREMENTS, RESULTS AND ANALYSIS

To study the effects of equivalence ratio and initial turbulence intensity on heat flux, simultaneous pressure and wall temperature data, and ionization probe signals were obtained over the range of test conditions shown in Table 4.1. The theoretical methods presented in Chapter 2 were then applied to each set of wall temperature data to obtain wall heat flux variations before and during the interaction of laminar and turbulent methane/air flames with the cold combustion chamber walls. The heat transfer coefficients for the unburned gas ahead of the flame were also calculated for every set of experimental data.

In this chapter, sample experimental measurements are presented along with calculated heat fluxes. The remainder of the experimental data and results are presented in Appendix B and Appendix C. A detailed discussion of the heat transfer correlations, comparison with other experimental results as well as the effects of heat flux on burning velocity are also given in this chapter.

Table 4.1

Experimental Conditions

Fuel/Oxidizer: Methane/Air

Laminar Flame Growth

Equivalence Ratio

P_{init} (atm)	0.6	0.75	0.85	1.0
0.5		x		x
1.0	x	x	x	x
1.5		x		x

Turbulent Flame Growth

Equivalence Ratio

Initial turbulence intensity (m/s)	0.6	0.75	0.85	1.0
0.5	x	x	x	x
1.0	x	x	x	x
1.5	x	x	x	x
2.0	x	x	x	x
2.5	x		x	x
3.0	x		x	x

4.1 Experimental Measurements

For laminar combustion, the temporal variation of pressure at an equivalence ratio of 1.0 is presented in Figure 4.1. Measurable pressure rise starts at approximately 10 ms after spark discharge. The maximum value of pressure occurs at approximately 60 ms. In Figure 4.2 the pressure variation for an equivalence ratio of 0.60 is shown. Here the duration of combustion is much longer, taking about 600 ms to complete.

The simultaneous wall temperature variation for an equivalence ratio of 1.0 is presented in Figure 4.3. The flame reaches the gauge at about 40 ms after ignition, as indicated by the steep temperature rise shown in Figure 4.3. This is followed by a small gradual increase to a maximum value due to the continuous burning of the remaining unburned mixtures. The same general results are also found for an equivalence ratio of 0.6. Here the flame speed is much slower so the sharp rise in temperature as the flame reaches the gauge, occurs much later, at approximately 300 ms (see Figure 4.4).

The wall temperature variations and ionization probe signals for an equivalence ratio of 1.0, with initial pressure 0.5 atm and 1.5 atm are shown in Figure 4.5 and 4.6. It is emphasized that the ionization probe signal proves that the steep temperature rise begins when the flame reaches the vicinity of the gauge (see Figure 4.5 and 4.6 of ionization probe signal combined with wall temperature variations). As

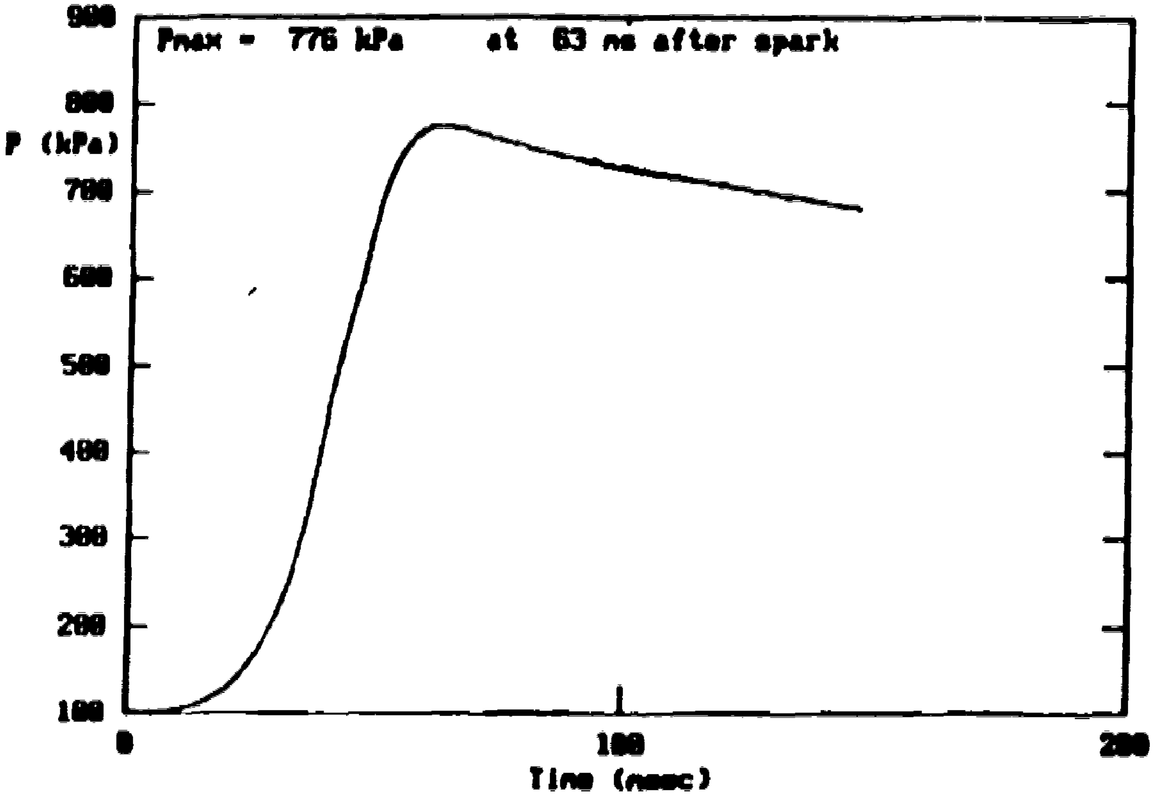

Figure 4.1 Pressure variation with time; laminar combustion; P_{init} = 1 atm; equivalence ratio 1.0.

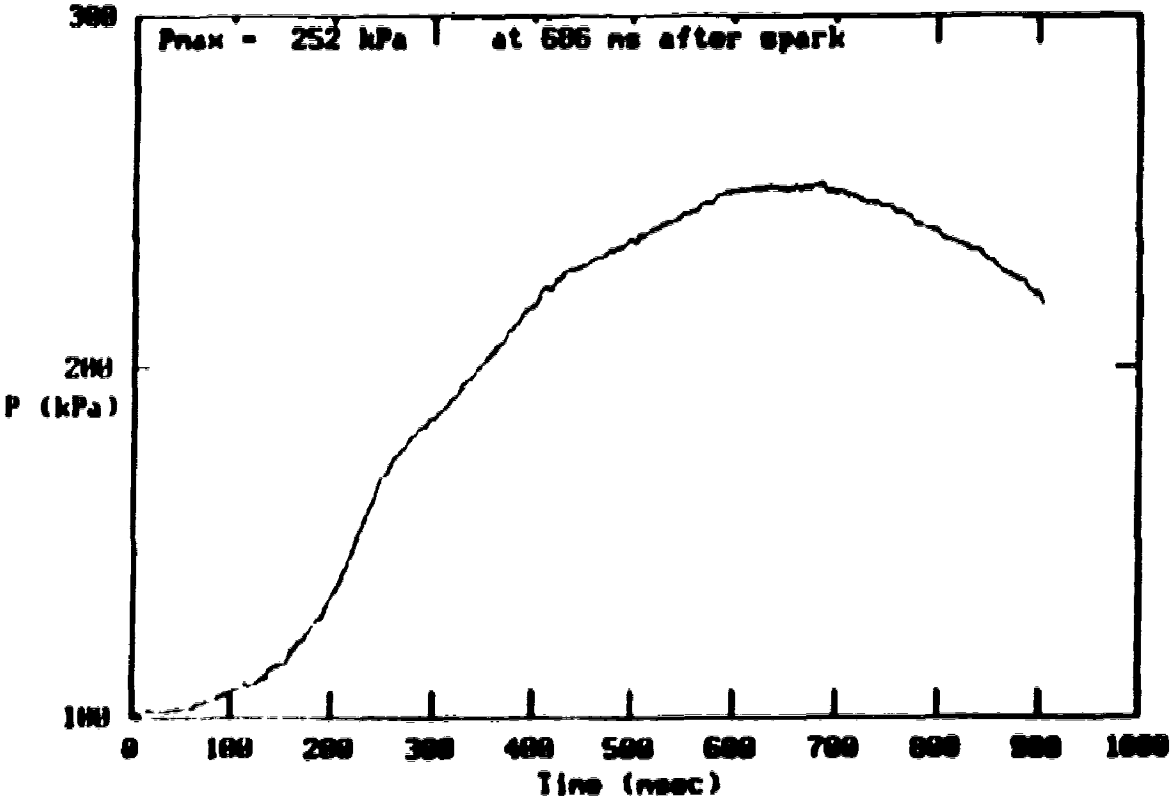

Figure 4.2 Pressure variation with time; laminar combustion; P_{init} = 1 atm; equivalence ratio 0.6.

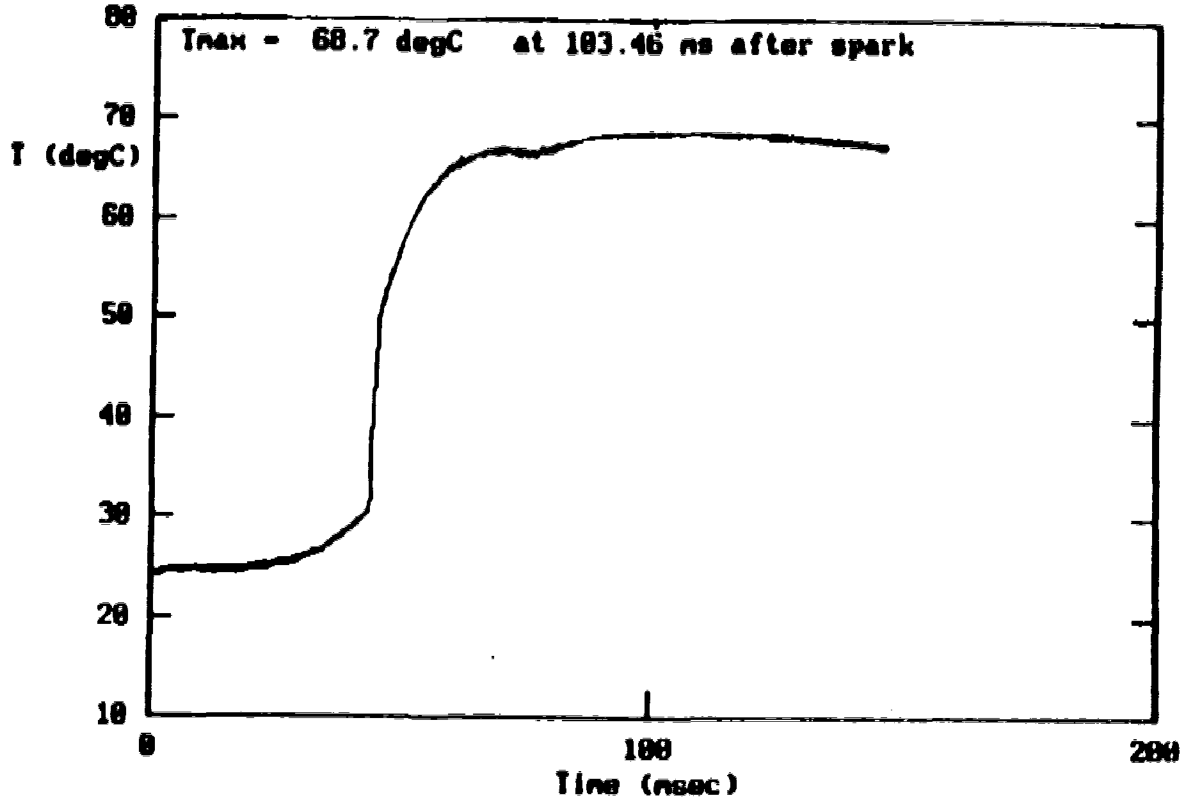

Figure 4.3 Wall temperature variation with time; laminar combustion; P_{init} = 1 atm; equivalence ratio 1.0.

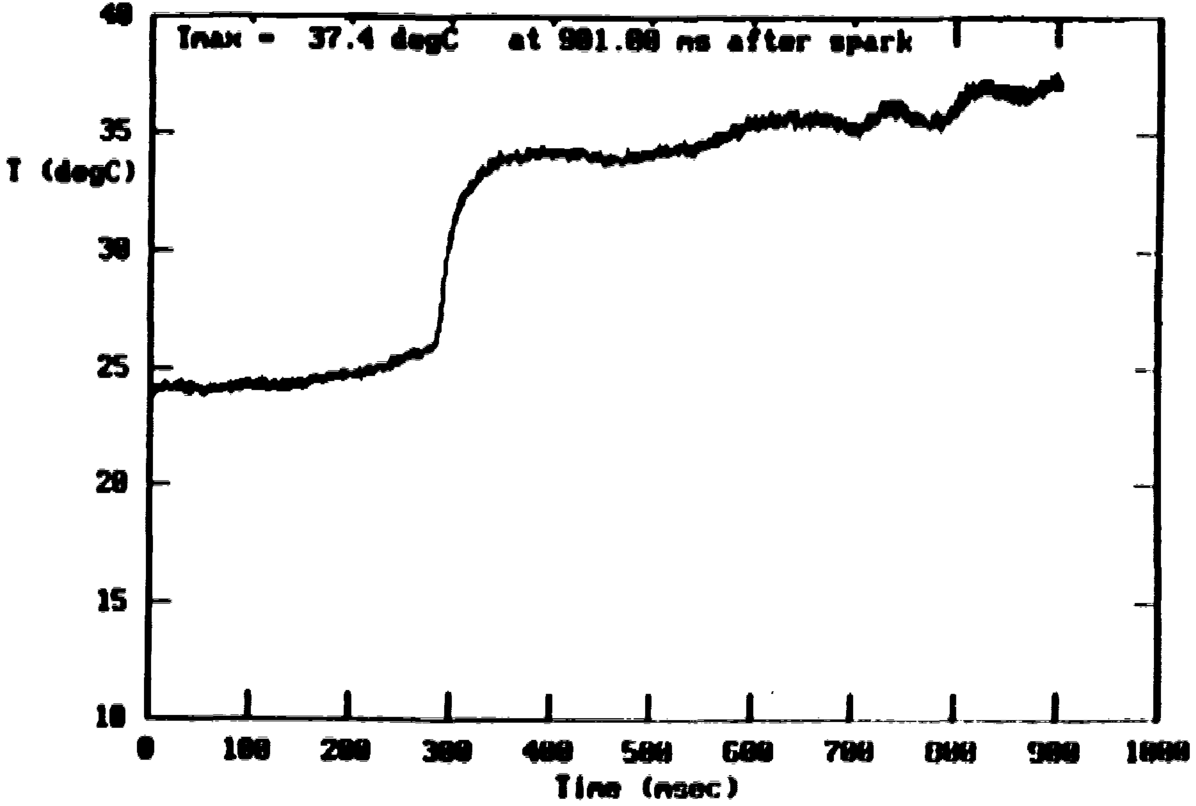

Figure 4.4 Wall temperature variation with time; laminar combustion; P_{init} = 1 atm; equivalence ratio 0.6.

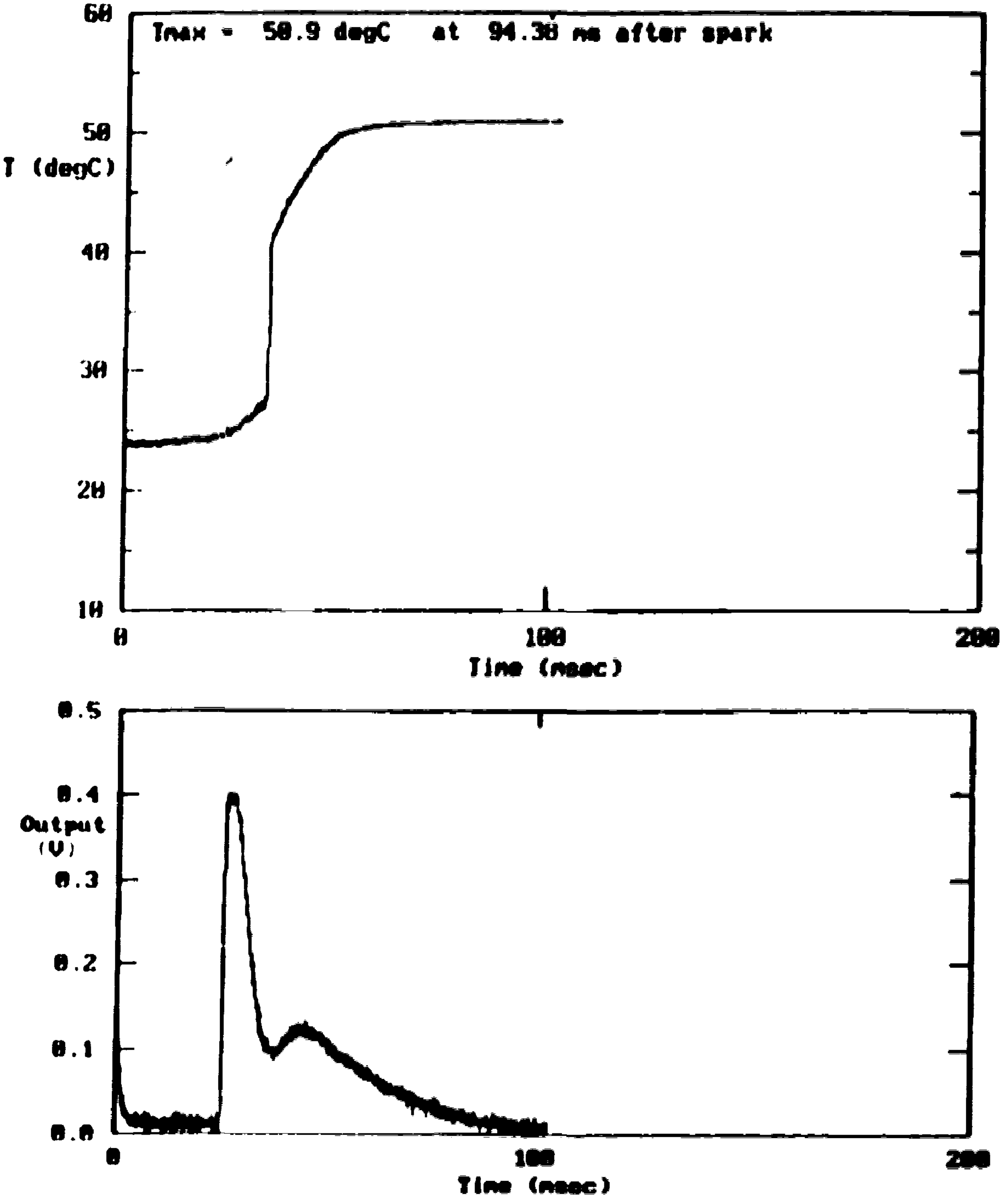

Figure 4.5 Wall temperature variation with time and ionization probe signal; laminar combustion; P_{init} = 0.5 atm; equivalence ratio 1.0.

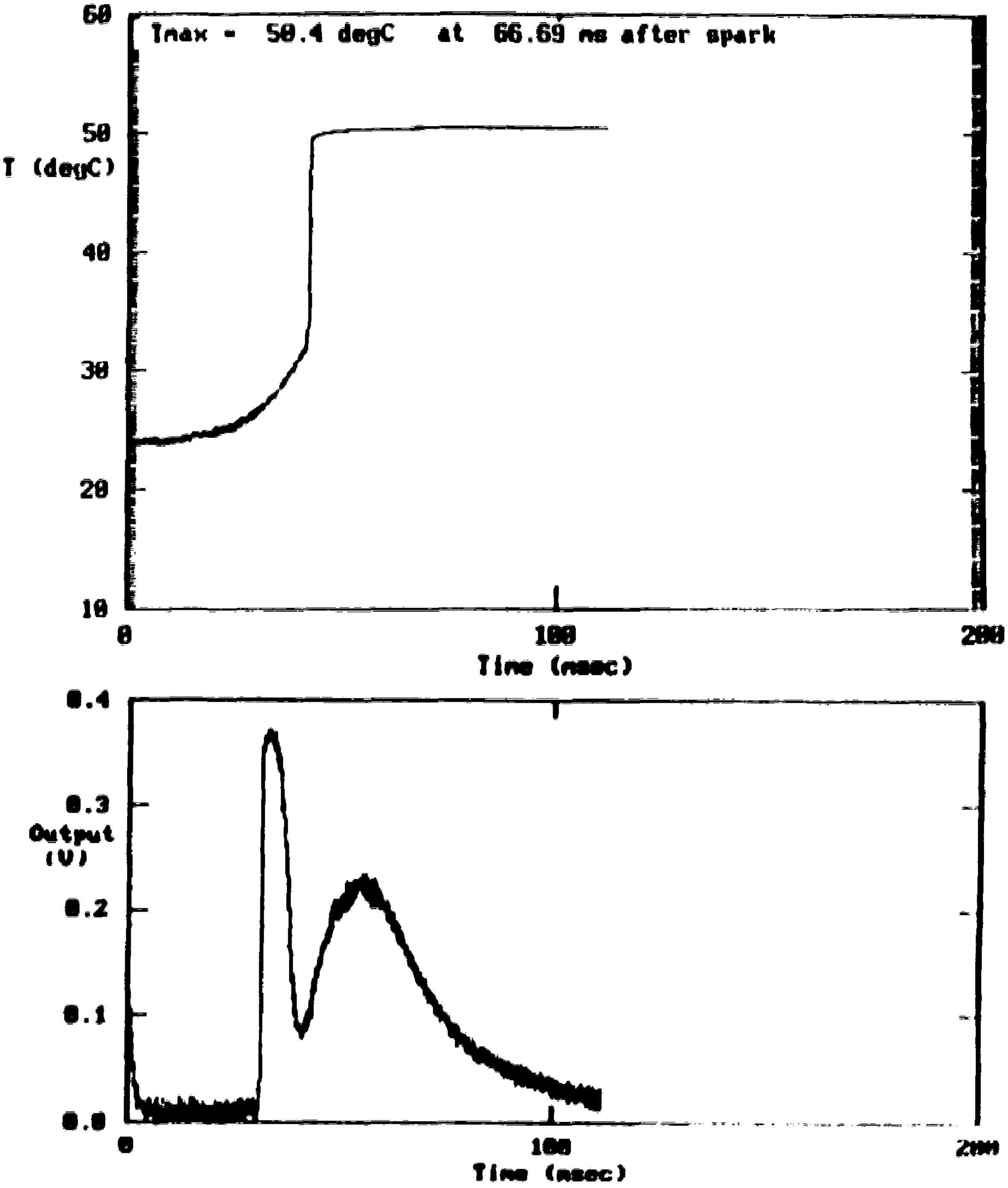

Figure 4.6 Wall temperature variation with time and ionization probe signal; laminar combustion; P_{init} = 1.5 atm; equivalence ratio 1.0.

shown in Figure 3.1 and 3.5, the ionization probe is at the center of the top wall and its tips are 2.5mm away from the cell wall. Thus a symmetrical flame would reach the probe before the heat flux gauge. This is shown in Figure 4.5 and 4.6.

For turbulent combustion, with an initial turbulence intensity 3.0 m/s, the pressure traces in Figure 4.7 and Figure 4.8 were obtained for equivalence ratio of 1.0 and 0.6, respectively. For both equivalence ratios, the maximum pressures occur much sooner than without initial turbulence due to the effect of turbulence on burning velocity [Ting, 1992]. The wall temperature variations were also obtained. The results for the combustion with initial turbulence intensity of 3.0 m/s are shown in Figure 4.9 and Figure 4.10 for equivalence ratio of 1.0 and 0.6 respectively.

4.2. Wall heat flux results

From the wall temperature measurements, heat flux variations were calculated. For laminar combustion, all of the results show similar trends as shown in Figure 4.11 - Figure 4.14. During the period before the flame reaches the gauge (e.g. before 40 ms after spark discharge for an equivalence ratio of 1.0, P_{in} = 1atm), the relatively cool

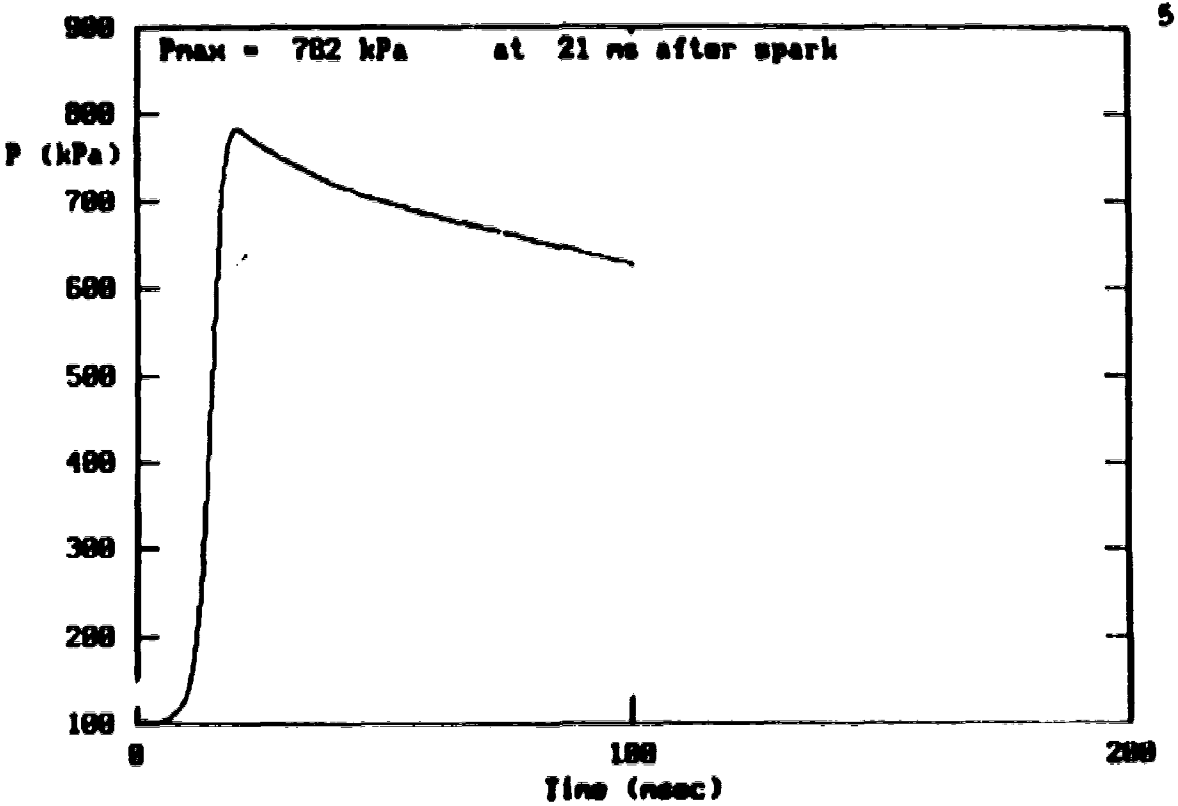

Figure 4.7 Pressure variation with time; initial turbulence intensity 3.0 m/s; P_{init} = 1 atm; equivalence ratio 1.0.

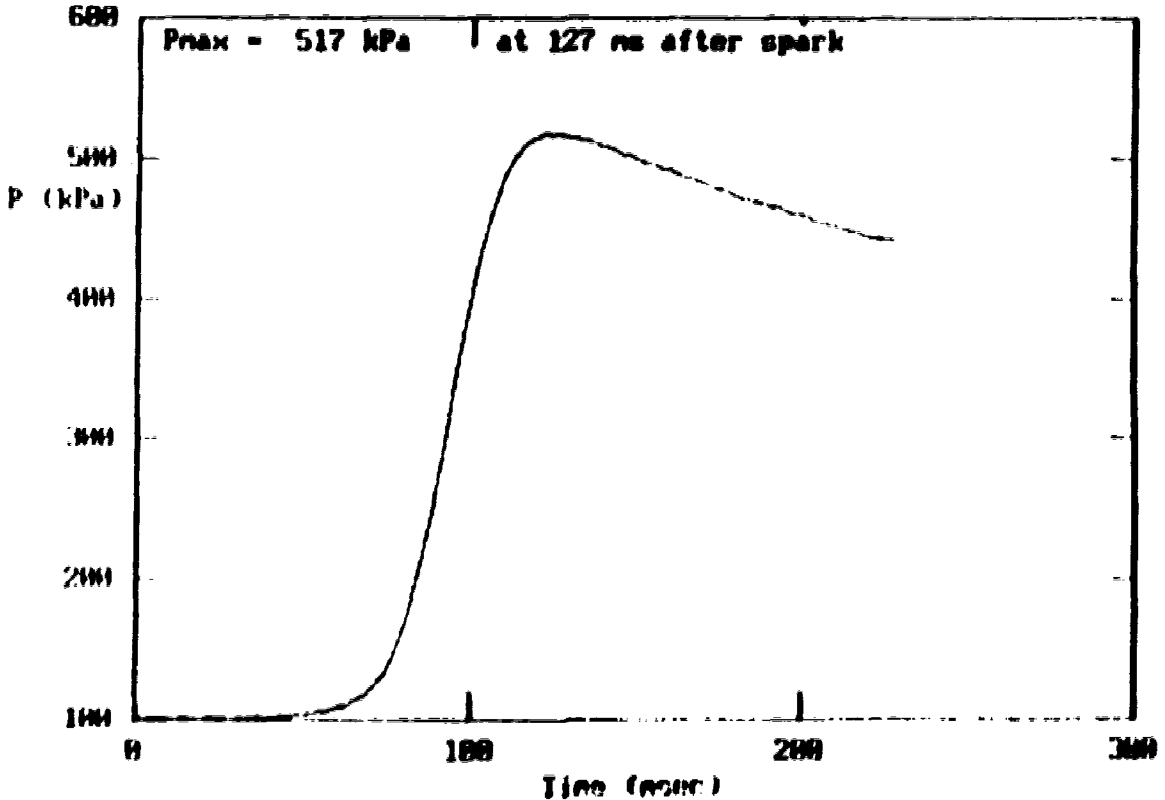

Figure 4.8 Pressure variation with time; initial turbulence intensity 3.0 m/s; P_{init} = 1 atm; equivalence ratio 0.6.

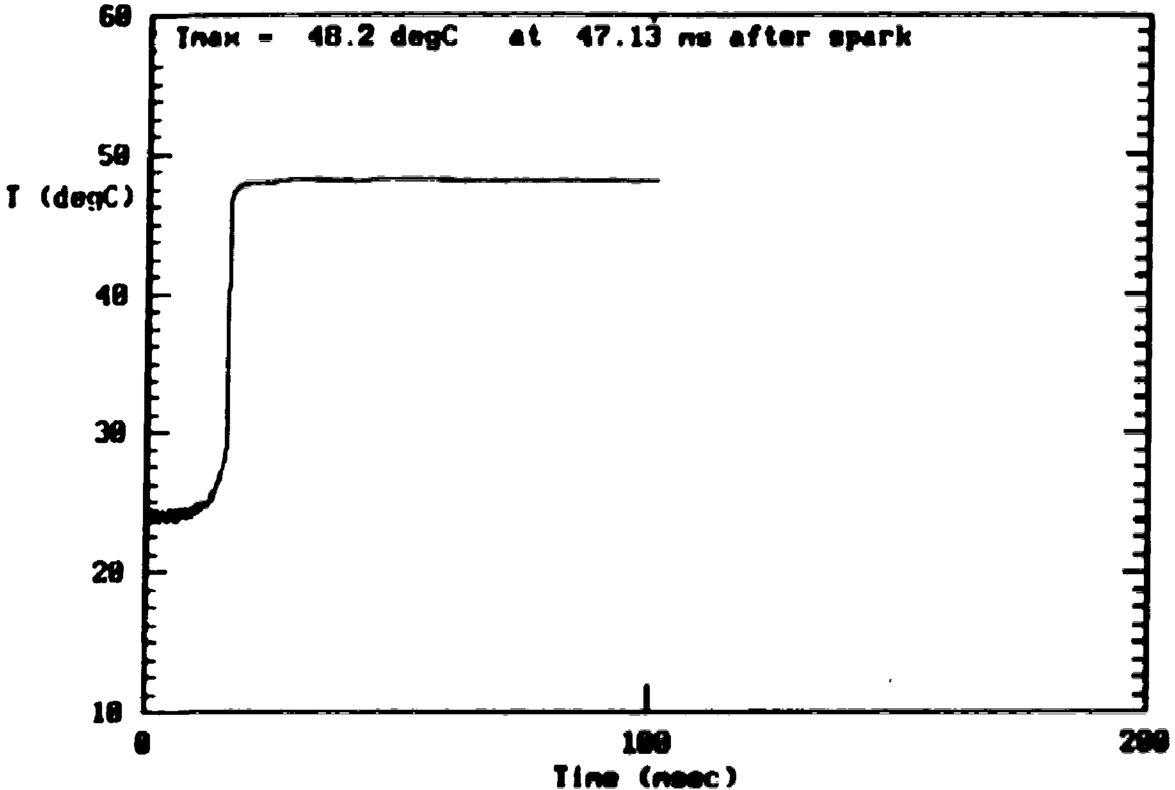

Figure 4.9 Wall temperature variation with time; initial turbulence intensity 3.0 m/s; P_{init} = 1 atm; equivalence ratio 1.0.

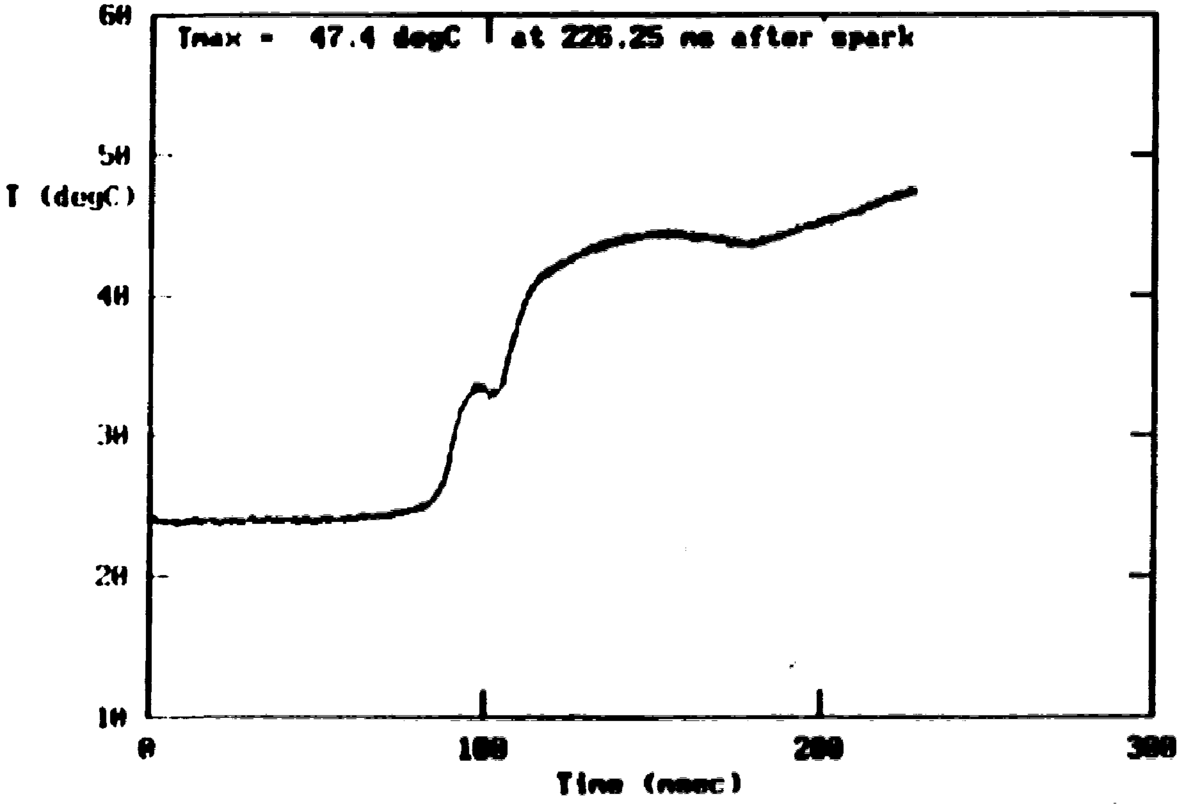

Figure 4.10 Wall temperature variation with time; initial turbulence intensity 3.0 m/s; P_{init} = 1 atm; equivalence ratio 0.6.

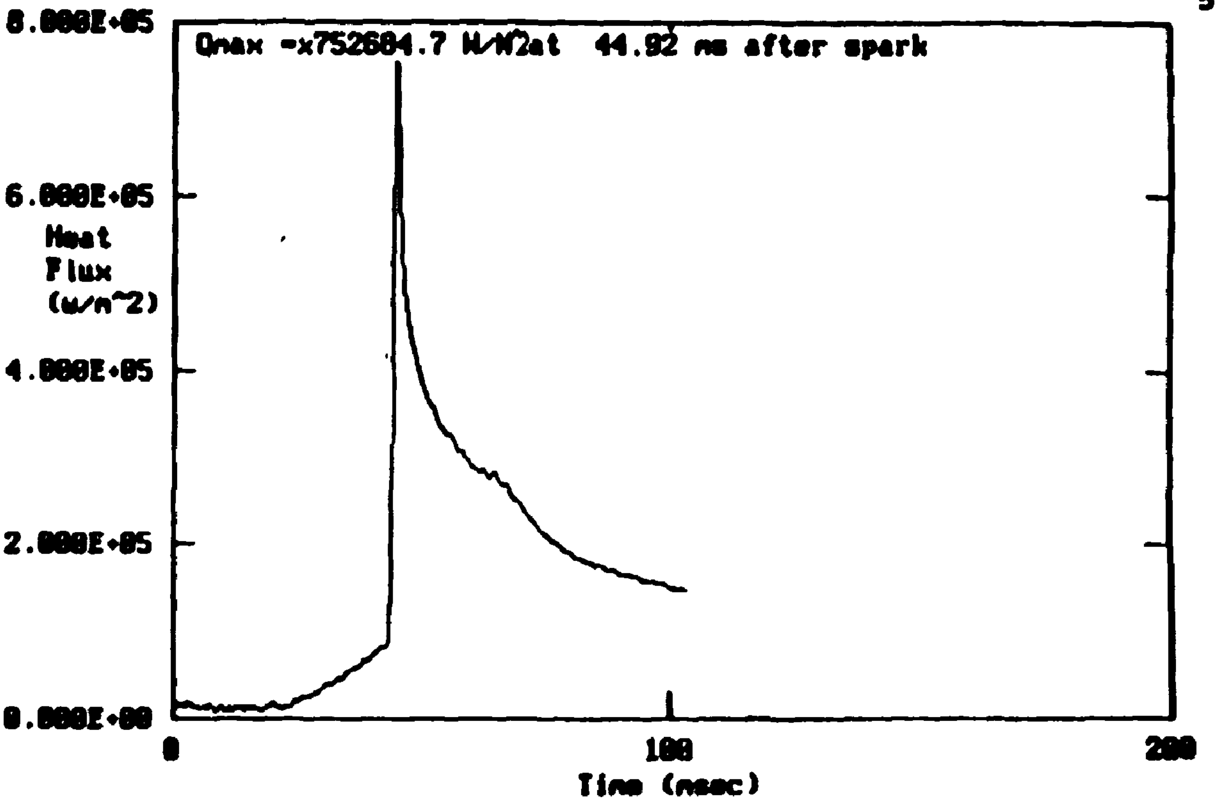

Figure 4.11 Wall heat flux variation with time; laminar combustion; P_{init} = 1 atm; equivalence ratio 1.0.

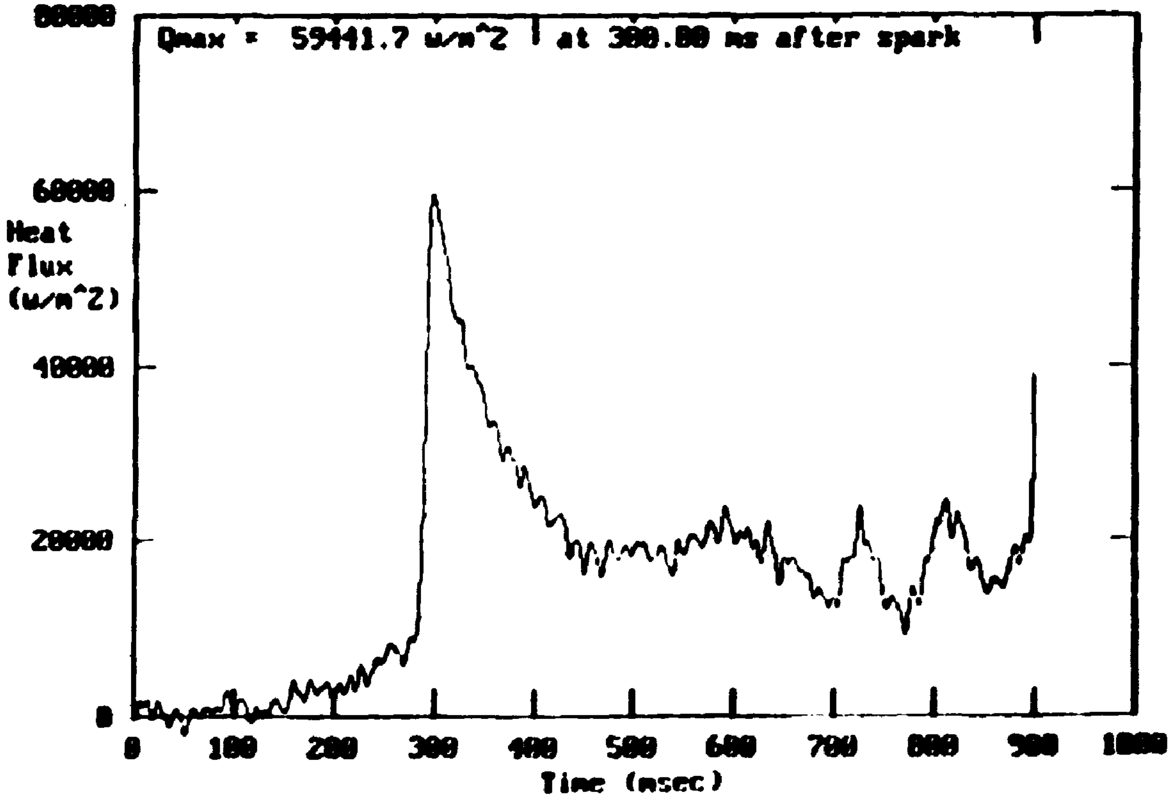

Figure 4.12 Wall heat flux variation with time; laminar combustion; P_{init} = 1 atm; equivalence ratio 0.6.

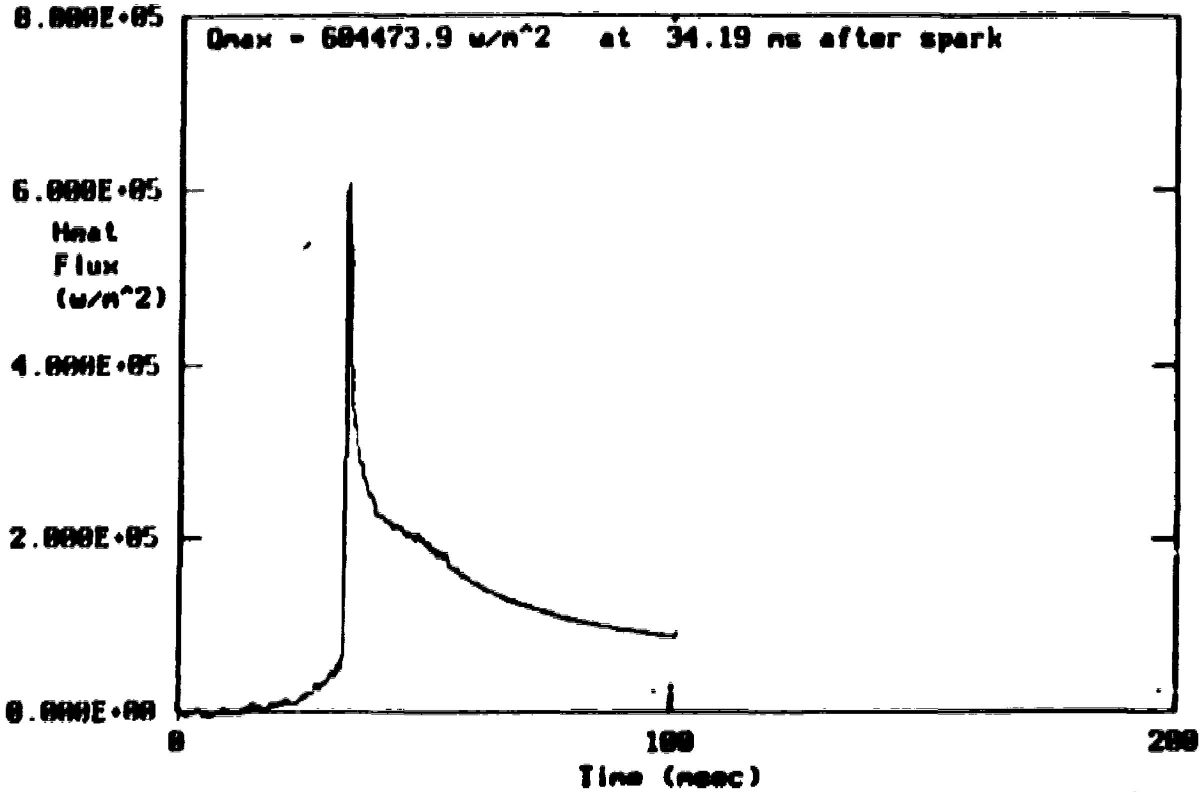

Figure 4.13 Wall heat flux variation with time; laminar combustion; P_{init} = 0.5 atm; equivalence ratio 1.0.

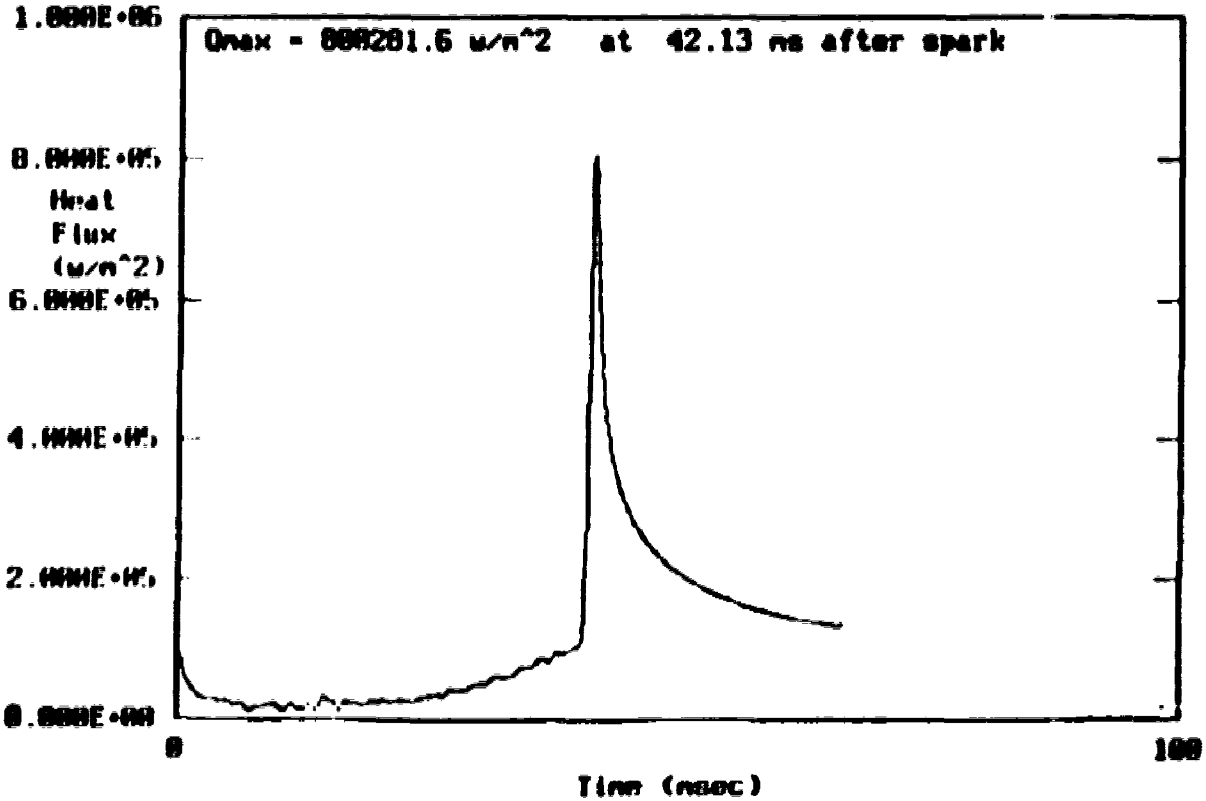

Figure 4.14 Wall heat flux variation with time; laminar combustion; P_{init} = 1.5 atm; equivalence ratio 1.0.

unburnt gases are being compressed by the combustion. This compression of the unburnt gas causes an increase in pressure and temperature, therefore, there is gradually increasing heat transfer from the unburnt gas to the wall. As the flame nears the gauge, the heat flux rises sharply to a maximum value. Then the heat flux starts to decrease with time due to the establishment of a thermal boundary layer and completion of the combustion. In Figure 4.12 the heat flux shows a sharp rise to a maximum value at a much later time than the stoichiometric case because of the much lower flame speed. The effects of initial pressure on peak heat flux are presented in Figure 4.15.

For the turbulent combustion cases, generally one prominent maximum value was found in the heat flux for most cases studied. More than one peak was also observed infrequently for cases with high turbulence intensity at the time of spark discharge. This second or third peak appeared because the high turbulence in the flame front sheers and distorts the flame front, and eddies of rapid motion transport burning and unburnt gases to the gauge surface. The heat flux results for equivalence ratio 1.0 and 0.6 with initial turbulence intensity of 3.0 m/s are presented in Figure 4.16 and Figure 4.17 respectively. By comparing them with laminar ones, it is seen that the peak wall heat flux is higher in turbulent combustion.

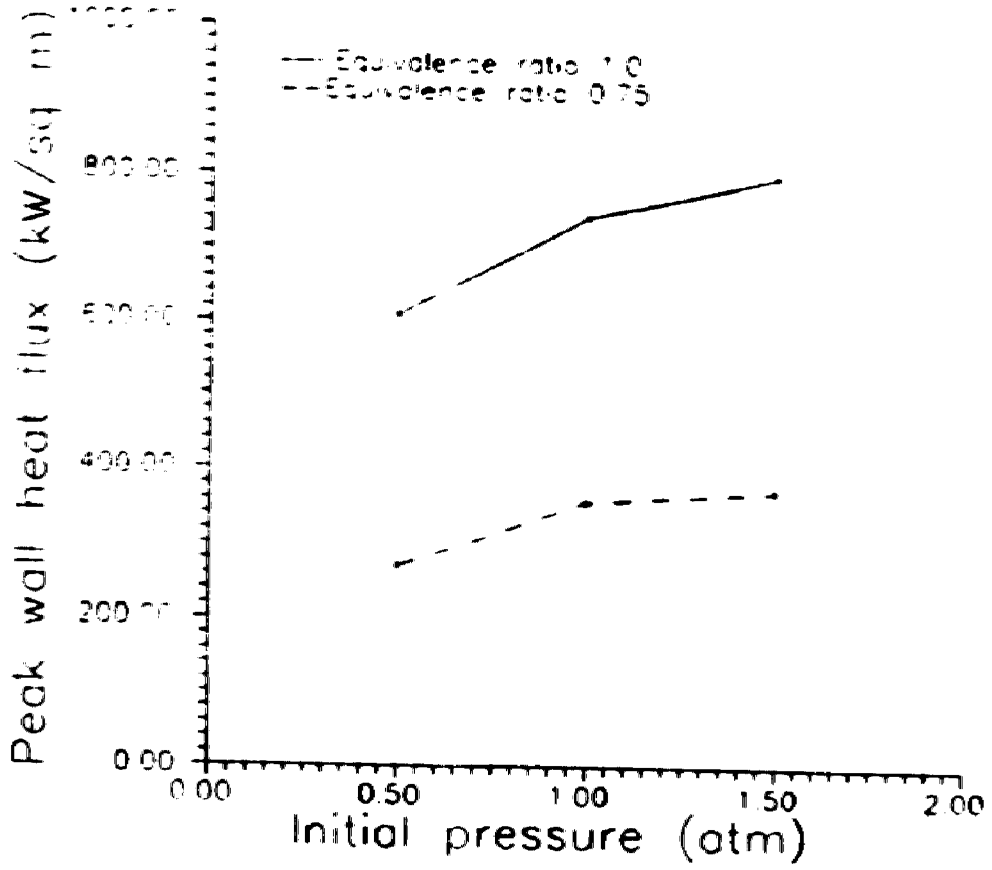

Figure 4.15 Peak wall heat flux variation with initial pressure; laminar combustion.

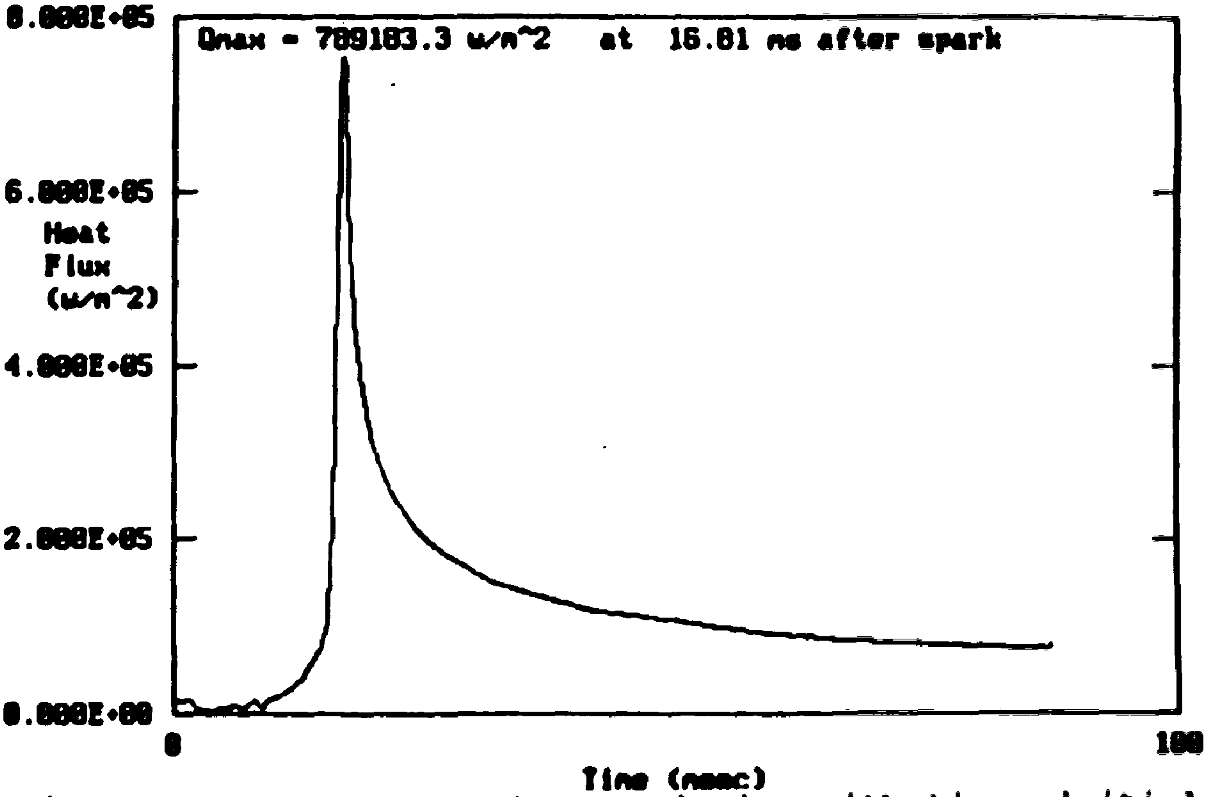

Figure 4.16 Wall heat flux variation with time; initial turbulence intensity 3.0 m/s; P_{init} = 1 atm; equivalence ratio 1.0.

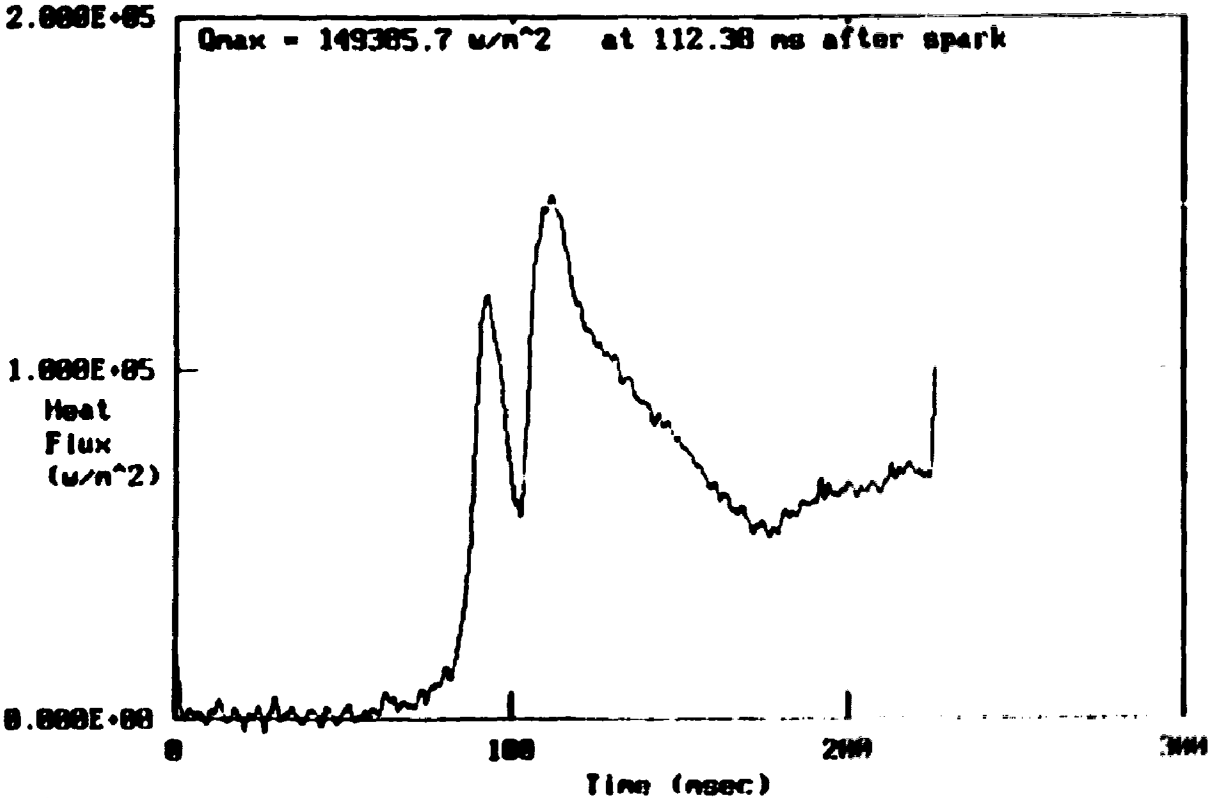

Figure 4.17 Wall heat flux variation with time; initial turbulence intensity 3.0 m/s; P_{init} = 1 atm; equivalence ratio 0.6.

4.3 Repeatability

To assess the repeatability of the experiment, several tests were made for identical experimental conditions and one set of laminar runs was repeated after doing the turbulent runs. The repeatability of the wall temperature variations for an equivalence ratio of 0.75, laminar combustion is presented in Figure 4.18. The run to run variation in the temperature rise is very small. The variation between runs made before and repeated after doing turbulent runs is of the order of seven percent. For corresponding heat flux results, the variation between runs made before and repeated after doing turbulent runs is of the order of nine percent (see Figure 4.19).

4.4 The Heat Transfer Coefficient

An average heat transfer coefficient for the unburned gas ahead of the flame was calculated for each set of experimental data using the measured wall temperature and the following equation

$$h = q/(T_u - T_w) \qquad (4.4\text{-}1)$$

Here q is the wall heat flux, T_u is the temperature of the unburnt gas, and T_w is the wall temperature. The multi-zone

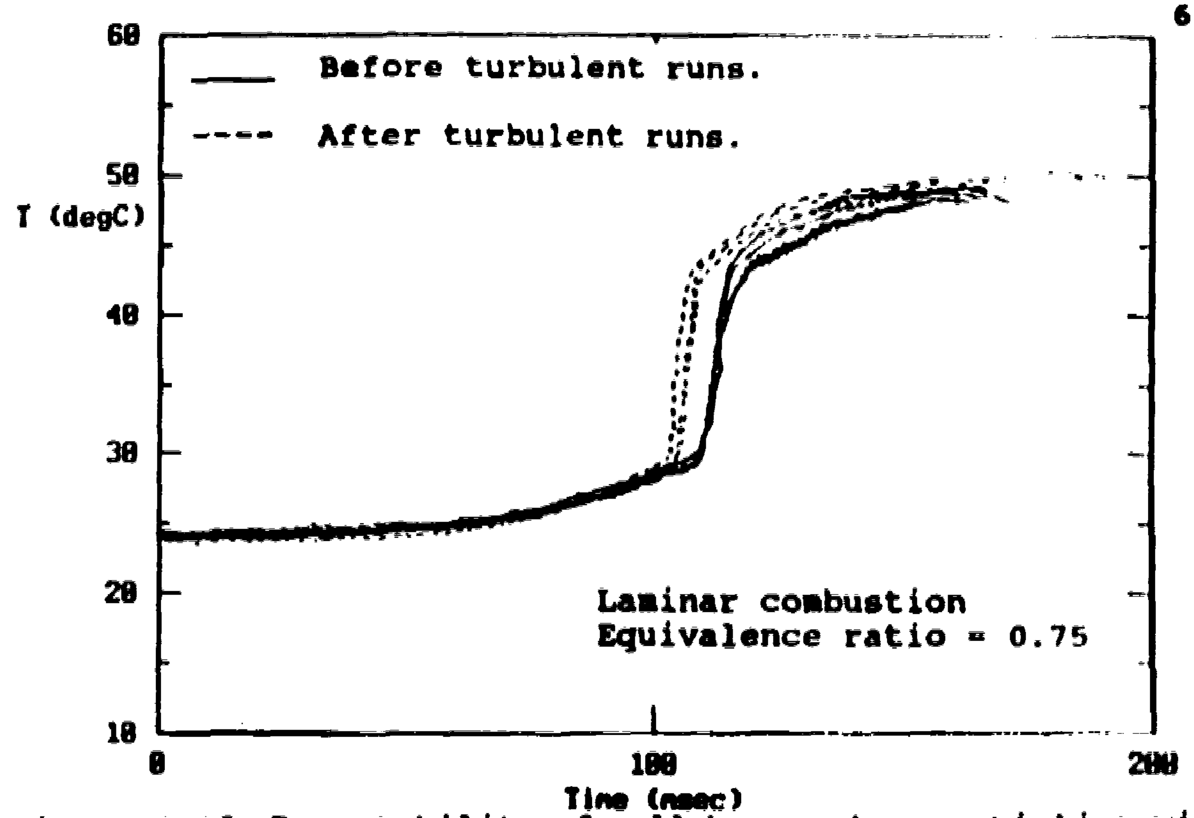

Figure 4.18 Repeatability of wall temperature variation with time; three measurements for identical conditions; P_{init} = 1 atm.

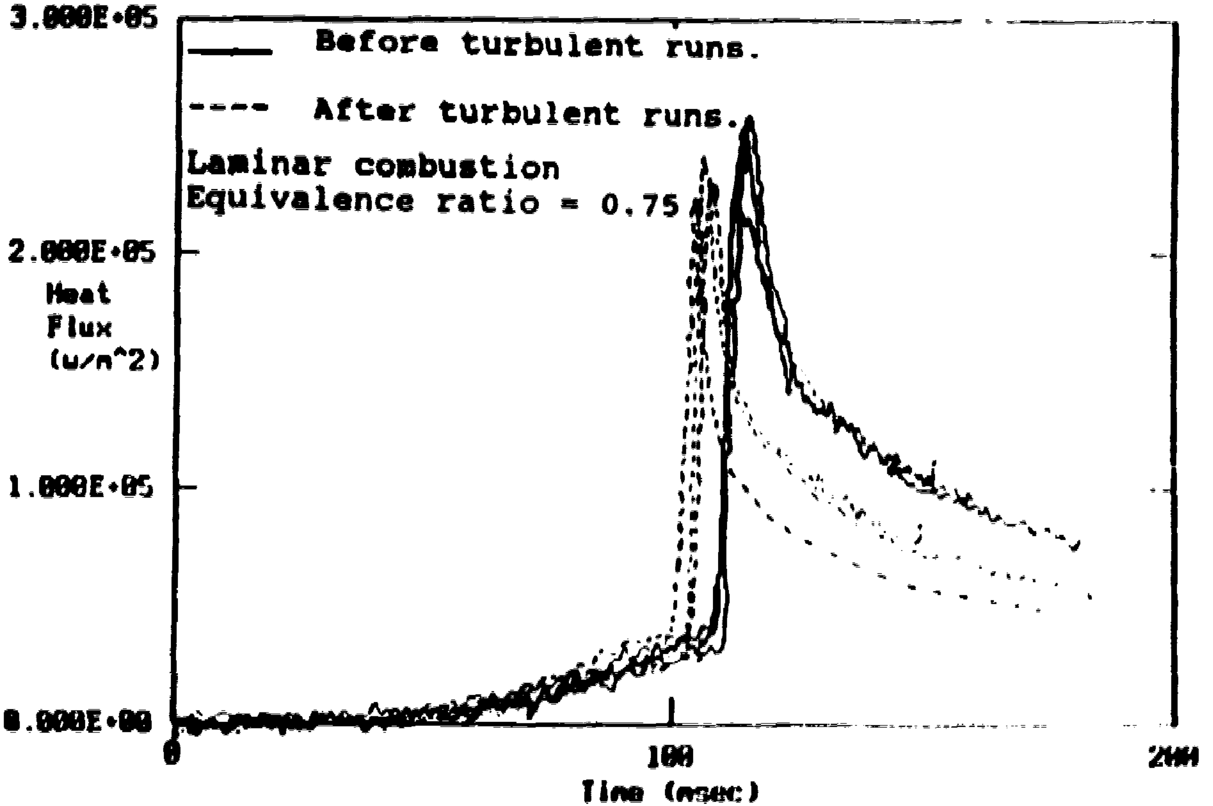

Figure 4.19 Repeatability of wall heat flux variation with time; three measurements for identical conditions; P_{init} = 1 atm.

thermodynamic equilibrium model [Modien, 1990; Ting, 1992] was used to calculate the unburnt gas temperature, T_u.

The values of the heat transfer coefficient for all of the experimental conditions listed in Table 4.1 are presented in Table 4.2. These are the average value of 2 to 5 consistent runs. The computer programs for calculations of the unburnt gas temperatures and the averaged heat transfer coefficients are given in Appendix A (parts 3 and 4).

Table 4.2

Calculated heat transfer coefficients

for laminar and turbulent combustion

from unburnt mixtures ahead of the flame front

		Equivalence ratio			
	h($W/m^2.K$)	0.6	0.75	0.85	1.0
Initial turbulence intensity (m/s)	0	155	244	326	451
	0.5	190	356	533	570
	1.0	255	472	461	506
	1.5	299	545	513	558
	2.0	331	653	536	586
	2.5	350	-	582	610
	3.0	414	-	668	643

4.5 The Heat Transfer Correlation

In forced turbulent fluid flow, the convective heat transfer is correlated in dimensionless groupings usually in the form

$$N_u = CRe^m$$

where C and m are constants. A turbulent Reynolds Number can be defined as

$$Re = \frac{u_0' L}{\nu}$$

where: u_0' = initial turbulence intensity

L = the characteristic unit of length

ν = kinematic viscosity

The measurements of heat transfer before the flame contacts with the wall, written as a Nusselt number,

$$N_u = \frac{hL}{k}$$

were correlated with this turbulent Reynolds number for all four equivalence ratios with six levels of turbulent intensity. The correlations are listed in Table 4.3. The characteristic unit of length L was defined as the distance from the center of the heat flux gauge surface to the centre of the cell. Figure 4.20 and Figure 4.21 show the correlation for an equivalence ratio 1.0 and 0.6 respectively. The remaining results are presented in Appendix D.

Table 4.3

Heat transfer correlations for combustion in a cubical cell before the flame strikes the wall

Correlation	Equivalence ratio
$N_u = 146.9Re^{0.25}$	1.0
$N_u = 94.7Re^{0.30}$	0.85
$N_u = 35.0Re^{0.43}$	0.75
$N_u = 19.5Re^{0.42}$	0.60

4.6 Comparison with Other Experimental Results

The variation in peak heat flux with equivalence ratio for laminar combustion is shown in Figure 4.22. The variations in heat flux with equivalence ratio observed in this study show the same trends as previous observations by Woodard (1982). In Woodard's study for constant volume combustion, the peak wall heat flux measurements were approximately 0.5 times lower than the values presented here, and the peak heat flux was observed to reach a maximum near stoichiometric conditions. The combustion chamber used by Woodard was not cubical.

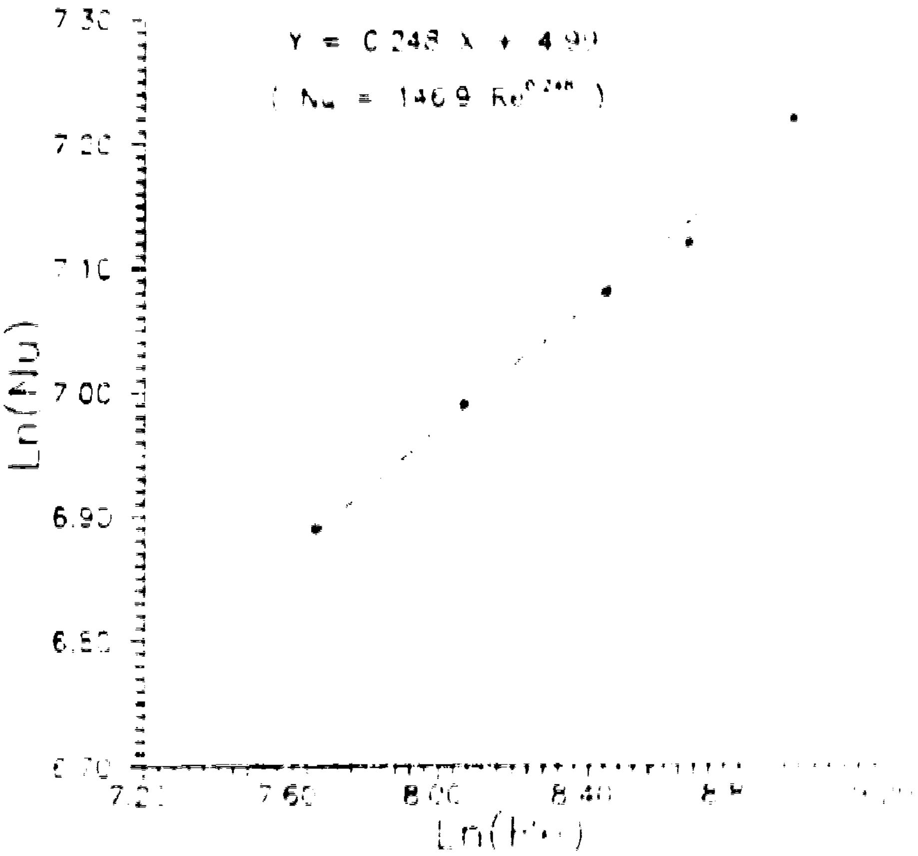

Figure 4.20 Wall heat transfer for turbulent combuston in a cubical cell before the flame contacts with the walls; equivalence ratio 1.0; P_{ini} = 1 atm.

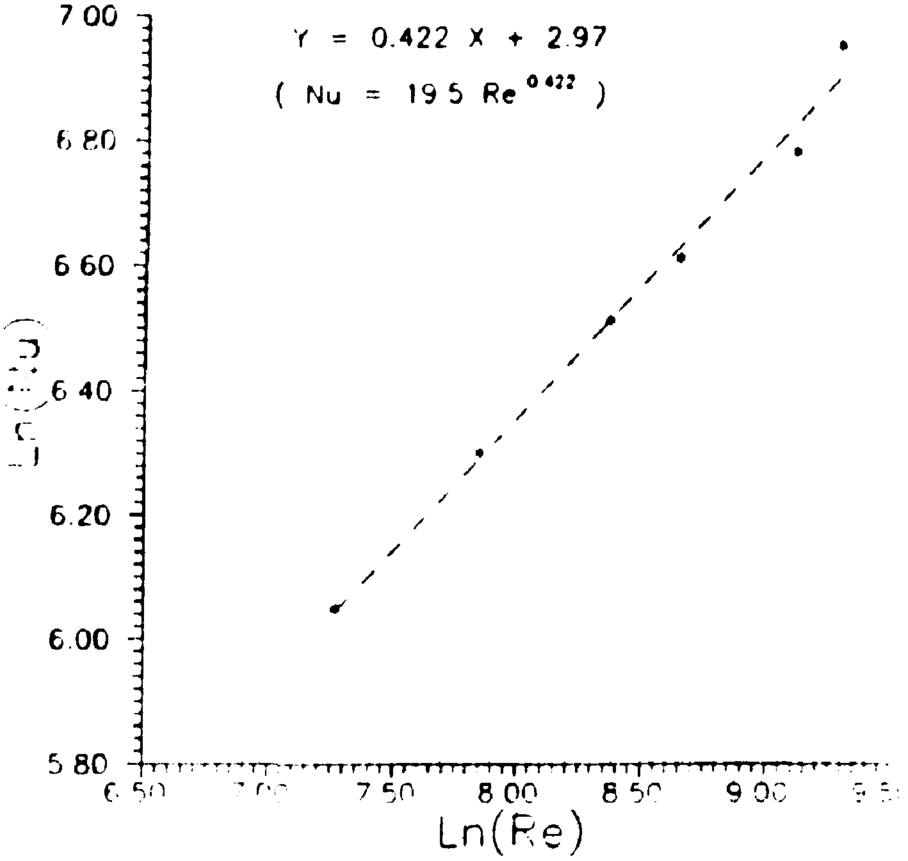

Figure 4.21 Wall heat transfer for turbulent combuston in a cubical cell before the flame contacts with the walls; equivalence ratio 0.6; P_{ini} = 1 atm.

Its length to cross section area was about 1/76mm compared with 1/125mm in this study. Flame initiation was at the center of one end of the chamber with heat flux measurements made at upper port far from the igniter where the flame was approximately perpendicular to the wall when passing the gauge.

The calculated heat transfer coefficients for unburnt gas ahead of the flame front agree well with Woschni's result found by repeating Nusselt's experiments in a spherical bomb with quiescent mixtures [Woschni, 1967]. In his experiments, the heat transfer coefficients were in the range of 0 to 400 kcal/m^2.h.°C, which is 0 to 460 W/m^2.K. Table 4.2 shows the heat transfer coefficients for quiescent mixtures in this study were within the same range (155 to 451 W/m^2.K).

Hoult, Hamiroune, and Keck (1987) found a rough heat transfer correlation between the heat transfer to the wall and the initial turbulence intensity for the end gas (i.e. the gas ahead of the flame) in a turbulent combustion bomb, as shown in Figure 4.23. It was based on the wall temperature and pressure measurements made for three levels of initial turbulence and performed with an equivalence ratio of 1.0. In this study, correlations of a form similar to those Equations shown in Figure 4.23 were found, as given in Table 4.3. The results from this study were based on measurements made for six levels

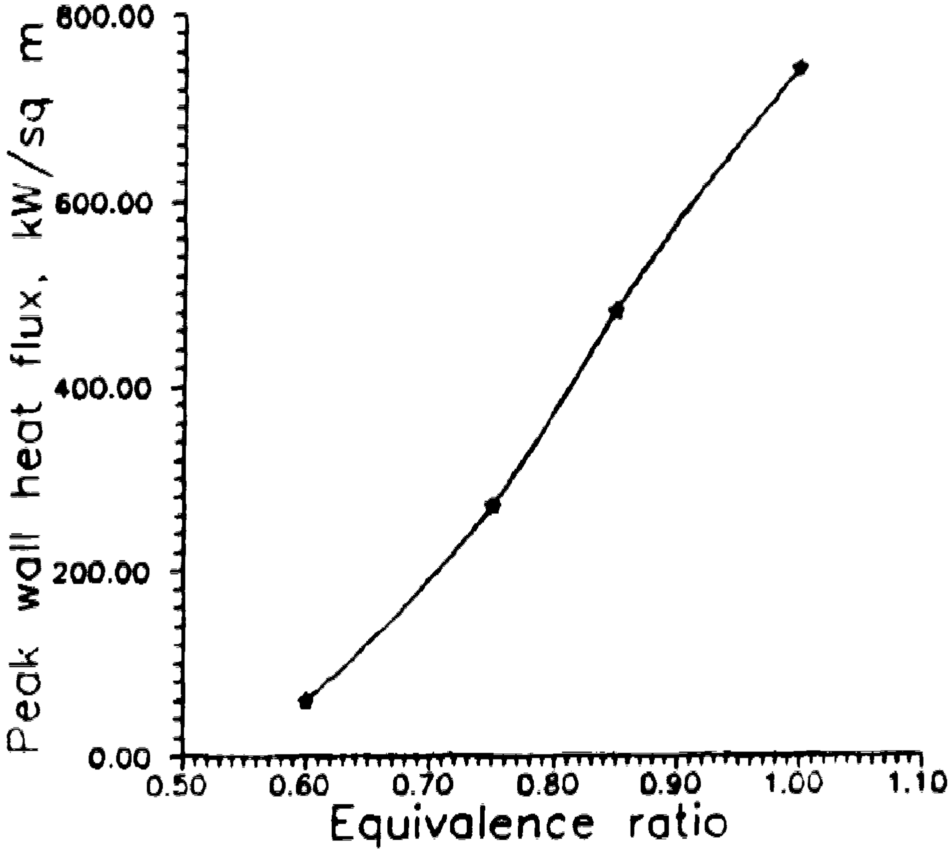

Figure 4.22 Peak heat flux variation with equivalence ratio; laminar combustion; P_{init} = 1 atm.

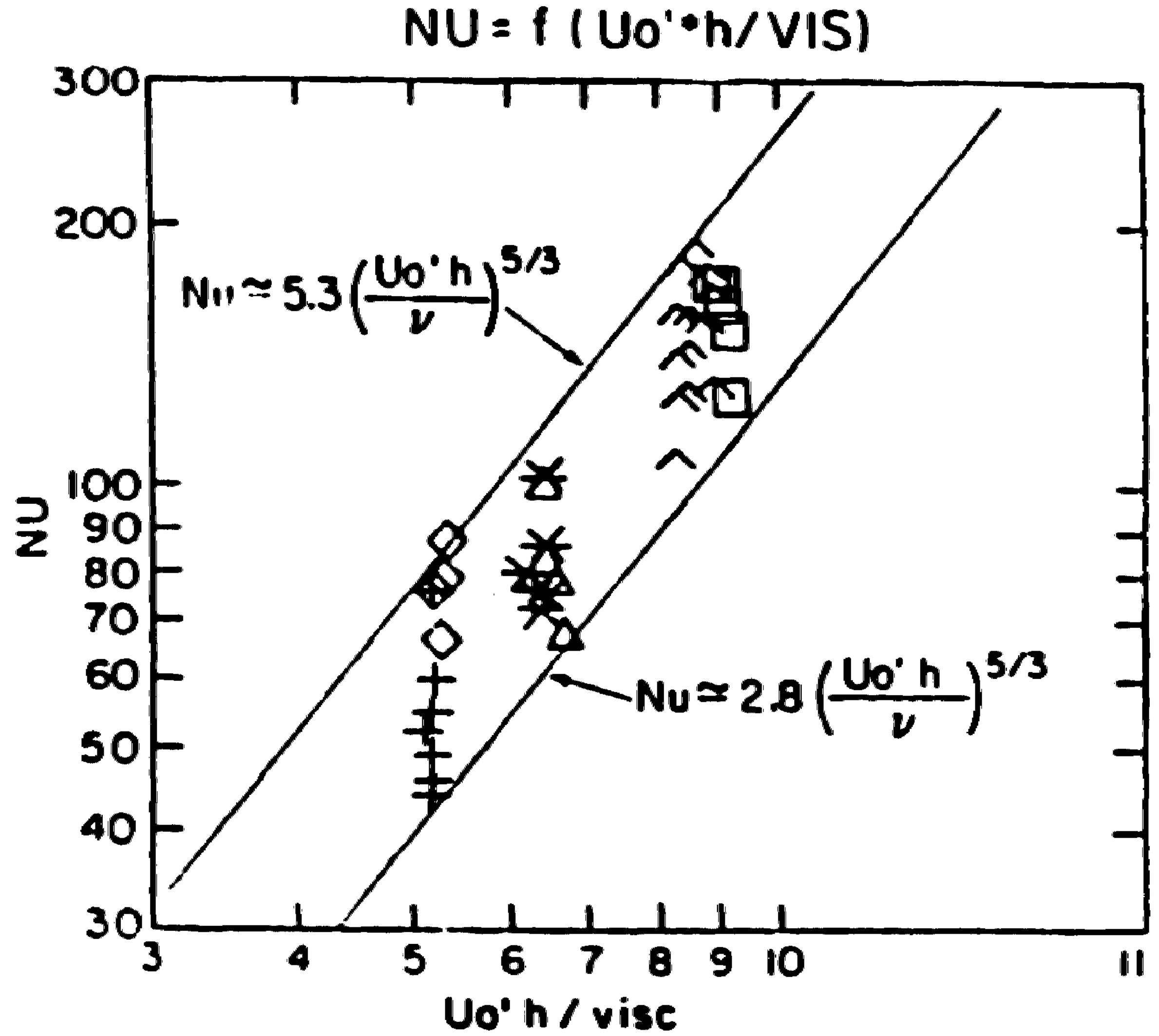

Figure 4.23 Effect of initial turbulent Reynolds number on Nusselt number; equivalence ratio 1.0; P_{in}=1atm. (From Reference Hoult, Hamiroune and Keck;1987)

of initial turbulence and four different equivalence ratios.

4.7 The Effects of Heat Flux on Burning Velocity Measurements

The burning velocity is defined as the velocity of the flame relative to the unburned gas ahead of the flame in the direction normal to the flame surface [Ting, 1992]. From a pressure trace, the burning velocity is calculated as the consuming rate of the unburnt gas between measurement points using multi-zone thermodynamic equilibrium model which assumes an adiabatic combustion wave propagating isotropically in the radial direction from the point of ignition [Modien, 1990; Ting, 1992]. This calculation ignores heat loss.

By applying experimental heat flux data directly, the burning velocity was calculated using a modified programme which takes the heat loss into consideration. Figures 4.24 and 4.25 respectively show the calculations of burning velocities with and without the measured heat loss being taken into consideration for the quiescent mixture of an equivalence ratio of 0.85. These preliminary results predict that the burning velocity is under predicted by 20% and 4% when the cell pressure is 115 kPa and 135 kPa respectively. For turbulent growing premixed flames, there are similar under-predictions by 2-5%, as shown in Figure 4.26 and 4.27 for pressure at 125kPa and 110kPa respectively.

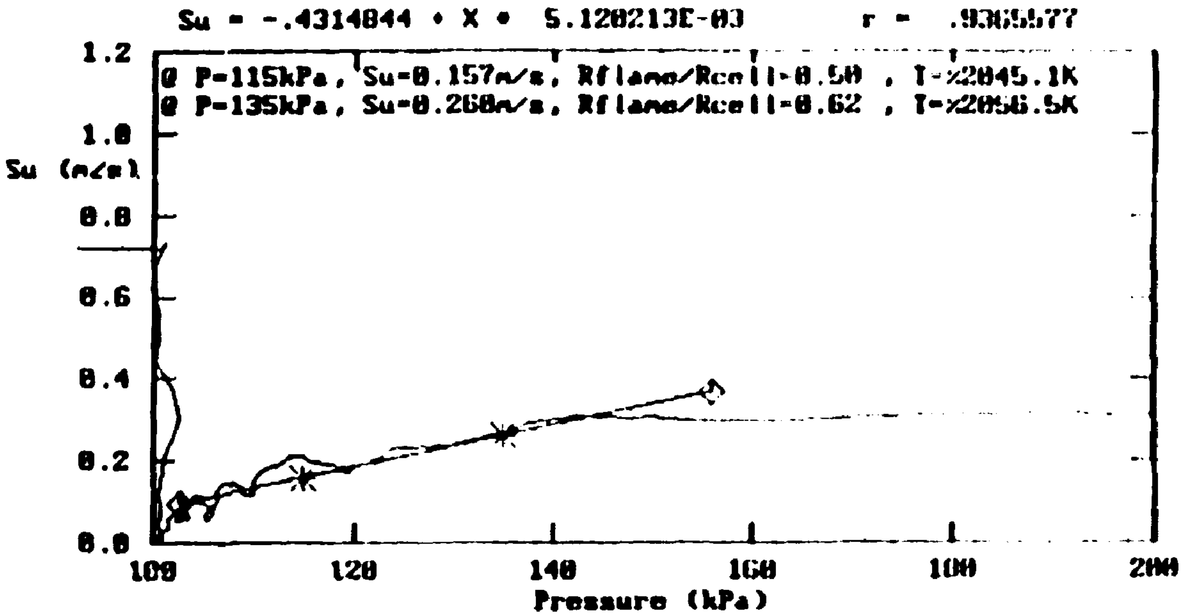

Figure 4.24 Calculated burning velocity without heat losses; laminar combustion; P_{init} = 1 atm; equivalence ratio 0.85.

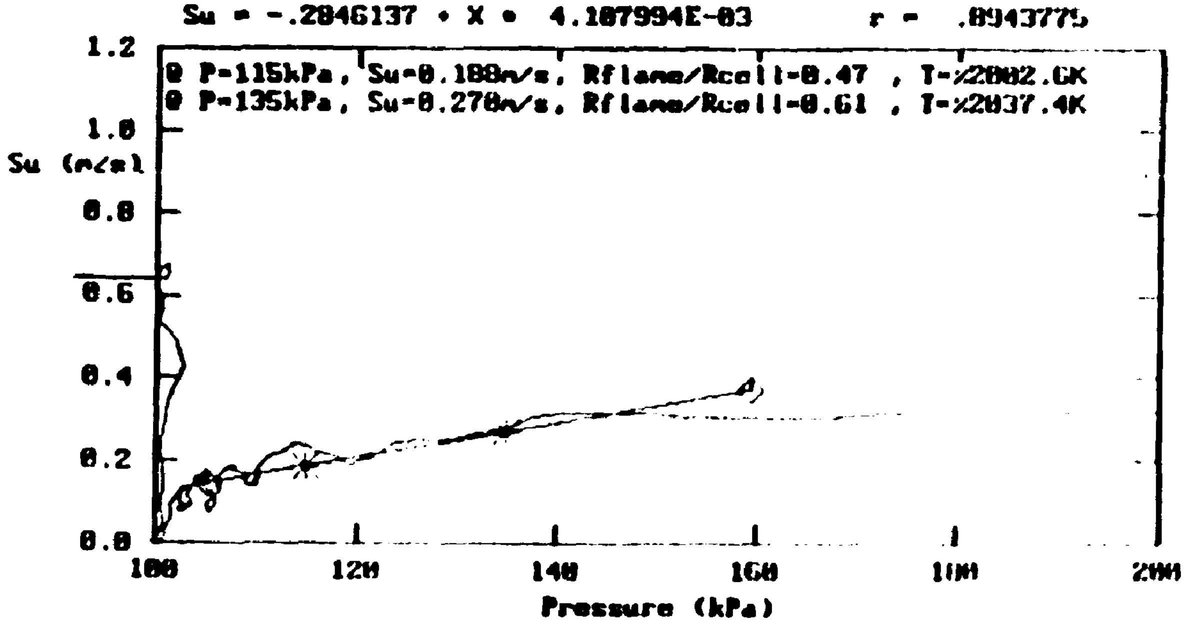

Figure 4.25 Calculated burning velocity with heat losses; laminar combustion; P_{init} = 1 atm; equivalence ratio 0.85.

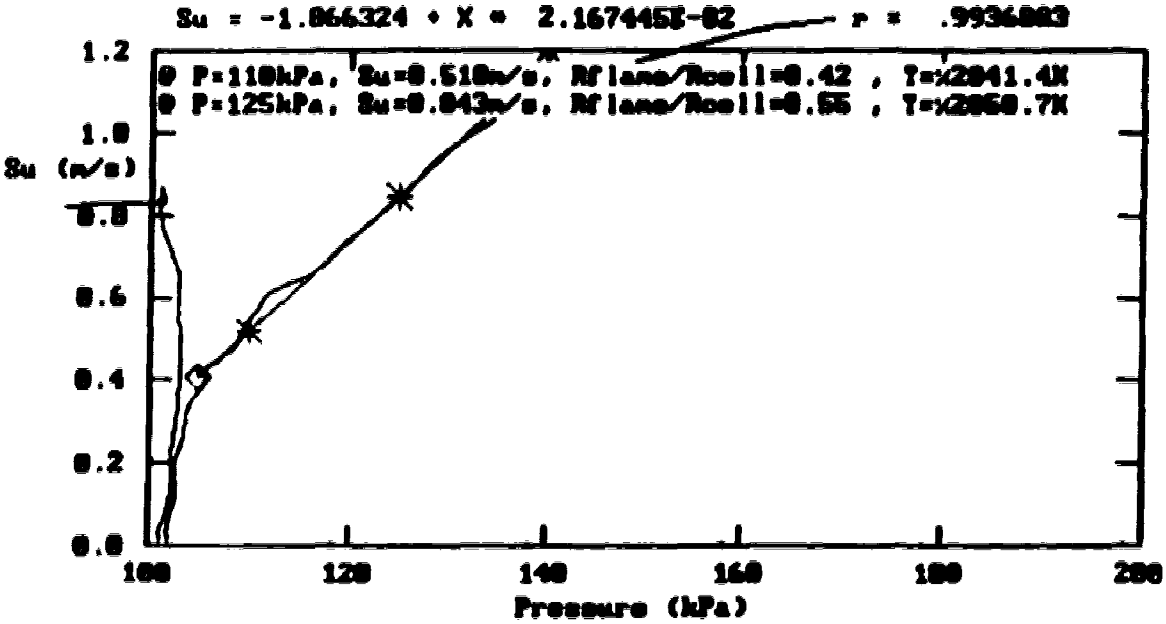

Figure 4.26 Calculated burning velocity without heat losses; initial turbulence intensity 3.0 m/s; P_{init} = 1 atm; equivalence ratio 0.85.

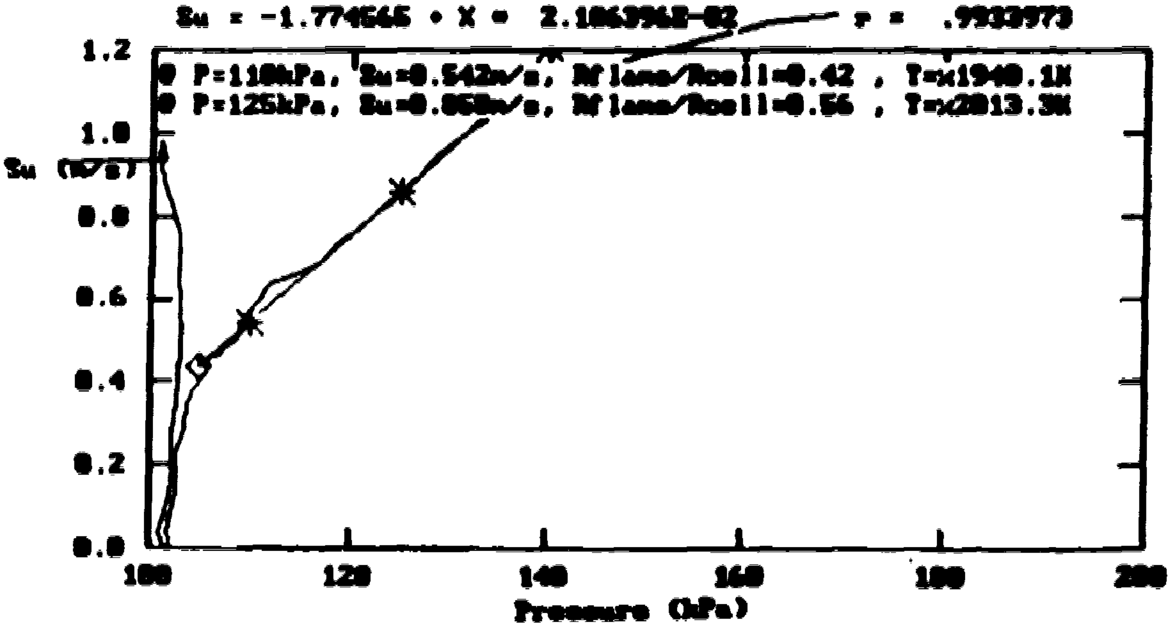

Figure 4.27 Calculated burning velocity with heat losses; initial turbulence intensity 3.0 m/s; P_{init} = 1 atm; equivalence ratio 0.85.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Experimental measurements and results of pressure, wall temperature, and wall heat flux were obtained for laminar and turbulent explosions of premixed methane-air mixtures in a cubical bomb. The experiments were performed over a range of equivalence ratios from 0.6 to 1.0. Based on the experiments performed in this study, it was found that:

1) The combustion cell wall temperature and the heat flux to the wall increase gradually before the flame strikes the wall, and then increase sharply when the flame reaches the heat flux gauge. The higher the equivalence ratio and initial turbulence intensity are, the sooner the sharp rises of the wall temperature and the heat flux occur.

2) The peak value of the heat flux varies considerably with equivalence ratio and the initial turbulence intensity. The higher the equivalence ratio and initial turbulence intensity, the higher the peak value. More than one heat flux peak may appear with a high initial turbulence intensity.

3) By defining a turbulent Reynolds number, the correlations between the heat transfer to the wall before the flame contacts with the wall and the initial turbulence intensity

for different equivalence ratios are as following:

$$N_u = 146.9Re^{0.25}\ ,\quad \text{equivalence ratio} = 1.0$$

$$N_u = 94.7Re^{0.30}\ ,\quad \text{equivalence ratio} = 0.85$$

$$N_u = 35.0Re^{0.43}\ ,\quad \text{equivalence ratio} = 0.75$$

$$N_u = 19.5Re^{0.42}\ ,\quad \text{equivalence ratio} = 0.60$$

4) When taking the heat loss into account, the burning velocities would be higher than predictions without consideration of heat loss. Preliminary results show the effect will be 2 to 20 % with most effect on very slow burning mixture (quiescient, very lean mixtures).

5.2.1 Recommendations for Further Research

Experiments performed over wide range of initial pressure are necessary in order to see the pressure effects on heat flux.

More heat flux gauges in different locations should be used so that a more complete view of heat fluxes for this cell and the effects of the gauge locations will be obtained.

To see how significant the effects of heat loss on burning velocity are, more work may be done using the correlations presented in Chapter 4 in order to eliminate the side effects of using the experimental data directly.

The same study may be conducted in the cylindrical cell and in the cubical cell with side ignition, where heat losses are considerably more important.

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APPENDIX A

The main computer programs used in this study are listed in this appendix. There are four parts:

1) the programs, 4ChPltP.bas and 4ChPltT.bas, which read and plot the digitized pressure and temperature data file and convert the original voltage input into pressure in kPa and temperature °C.

2) the heat flux calculation program using the Duhamel's formula and the trapezoidal rule - QGAUGEBM.bas.

3) the multi-zone thermodynamic equilibrium modelling program for the calculation of the unburnt gas temperatures - EBMBPR2.bas.

4) the averaged heat transfer coefficient calculation program - htCoef.bas.

PART 1

```
DECLARE SUB Filter (i!(), f!(), n%, COV%)
'
'      4ChPltP.bas
'      ***********
'
'
'      Oct 15 1992    DSK TING
'
' This program reads, plots and saves pressure data generated
' by digitization.
'
   REM $INCLUDE: 'C:\QB\LIB\PLOTCOM.BAS'
   REM $INCLUDE: 'C:\QB\LIB\COLORCHC.BAS'
   REM $DYNAMIC
' Dimension some arrays.
   REDIM dcom$(20), dpar$(20), dpar!(20), dd!(20, 20)
' Set up the graphics screen.
   SCRN% = 9
' Get the data file.
   DFN$ = "1"
GETFILE:
   DF$ = "C:\QB\DAS16\DATA\" + DFN$ + ".dat"
   CLS : PRINT "Enter file name. (Enter= "; DF$; ")  >";
   INPUT DF1$
   IF DF1$ <> "" THEN
     DFN$ = DF1$
     GOTO GETFILE
   END IF
   GOSUB YESFILE
' Set # rows and # columns
   NROW% = DNR%
   NCOL% = DNC%
PLOTWHAT:
   CLS : INPUT "Enter column # for Y. (Enter=3) > "; coly
   IF coly = 0 THEN coly = 3
   IF coly <> 0 THEN coly = coly
' Search the starting (SPARK) point
   FOR i = 2 TO DNR%
     IF dd!(i, 4) > 500 THEN
        Ifirst = i + 4    'avoid the spark interference
        GOTO STARTLOOP
     END IF
   NEXT i
STARTLOOP:
' Read Y and X data.
   n% = DNR% - Ifirst - 1
```

```
   REDIM X(n%), Y(n%)
   FOR i = 1 TO n%
     X(i) = dd!(i + Ifirst, 1) - dd!(Ifirst, 1)
     Y(i) = dd!(i + Ifirst, coly
   NEXT i
'
IF coly > 3 THEN GOTO Plotting
' Filter Y(i) to smooth it out.
'
   REDIM XYF(n%)
   NUMFILT = 0
   NCOV% = 3
FILTER2:
   IF NUMFILT < 2 THEN
     CALL Filter(Y(), XYF(), n%, NCOV%)
     FOR i = 4 TO n%
        Y(i) = XYF(i)
     NEXT i
     NUMFILT = NUMFILT + 1
     NCOV% = NCOV% - 1
     GOTO FILTER2
   END IF

' **************Change to suit****************
' Convert pressure to V and then to kPa
   IF coly < 3 THEN
     FOR i = 1 TO n%
        Y(i) = .001964 * Y(i) - .001677
     NEXT i
   ELSE
     FOR i = 1 TO n%
        Y(i) = .004945 * Y(i) - .04835
     NEXT i
   END IF
'
   PRINT "Initial pressure (V) = "; Y(5); " V"
   INPUT "Okay ? (Enter = Yes/Continue, 2 = No/Stop)"; ok%
   IF ok% <> 0 THEN STOP
   PRINT "Y(kPa) = a * Y(V) + b"
   INPUT "a ="; a!
   INPUT "Initial pressure (kPa) = "; Pinit!
   b! = Pinit! - a! * (Y(4) + Y(5) + Y(6)) / 3
   PRINT "b ="; b!
   FOR i = 1 TO n%
       Y(i) = a! * Y(i) + b!
   NEXT i
```

```
    Pjk = (Y(4) + Y(5)) / 2!
    PRINT "Initial pressure (kPa) = "; Pjk; " kPa"
    INPUT "Okay ? (Enter = Yes/Continue, 2 = No/Stop)"; ok2%

    IF ok2% <> 0 THEN STOP
 ' Maximum pressure rise (kPa)
    IF coly = 3 THEN
      Pmax = 0
      FOR i = 2 TO n% - 3
         Yavg = (Y(i - 1) + Y(i) + Y(i + 1)) / 3!
         IF Yavg > Pmax THEN
           Pmax = Yavg              ' Pmax (kPa)
           tPmax = X(i)             ' Time at Pmax (ms)
           iPmax% = i
         END IF
      NEXT i
    ELSEIF coly = 2 THEN
      Pmax = 0
      FOR i = 2 TO n% - 3
         Yavg = (Y(i - 1) + Y(i) + Y(i + 1)) / 3!
         IF Yavg > Pmax THEN
           Pmax = Yavg              ' Pmax (kPa)
           tPmax = X(i)             ' Time at Pmax (ms)
           iPmax% = i
         END IF
      NEXT i
    END IF
Plotting:
'-------------------------
' Data plotting section.
PLOTSECTION:
   XLB$ = "Time (msec)"
   YLB$ = "P (kPa)"
   SCREEN 0: WIDTH 80: COLOR 15, 1
   CLS : PRINT "Plotting"
   INDAX% = 0: XSUB% = 0: YSUB% = 0
   CALL AXES(X(), Y(), n%, XSUB%, YSUB%, Xmn, Xmx, Xdv, NXS%,
Ymn, Ymx, Ydv, NYS%)
   Ymn = 100: Ydv = 100
   Xmn = 0!: Xdv = 10: Xmx = 200
'
LINETYPE:
   LIN% = 1
   CHAR% = 0
   CALL PINI(SCRN%, 1): c% = ngc%
   CALL YAXIS(Ymn, Ymx, Ydv, YSUB%, NYSUBD%, YLB$, Y2$, Y3$,
```

```
c%)
  CALL XAXIS(Xmn, Xmx, Xdv, XSUB%, NXSUBD%, XLB$, c%)
'
PLOTMORE:
  CALL LINPLT(X(), Y(), n%, CHAR%, 1, 6!, c%)
  LOCATE 3, 15: PRINT " File " + DF$
  LOCATE 5, 14: PRINT USING " Pmax =##### kPa"; Pmax
  LOCATE 5, 34: PRINT USING " at ### ms after spark"; tPmax

'-------------------------
' Finished plots, now what?
'
OPTIONS:
   LOCATE 1, 1
   INPUT " 0=hard copy, 1=quit, 2=restart, 3=change Y,
4=save >"; opt
   IF opt = 4 THEN GOTO SAVE
   IF opt = 3 THEN GOTO PLOTWHAT
   IF opt = 2 THEN GOTO GETFILE
   IF opt = 1 THEN SCREEN 0: COLOR 15, 1: CLS : END
   IF opt = 0 THEN CALL PHCOPY(xyz$)
'
SAVE:
   SFN$ = DFN$ + "p"
   SF$ = "C:\QB\MING\MSC\PDATA\" + SFN$ + ".dat"
filename:
   CLS : PRINT "ABOUT TO WRITE TO "; SF$
   INPUT "ENTER = GO ON, ELSE ENTER A NEW FILE NAME.>";
SFN1$
   IF SFN1$ <> "" THEN
      SFN$ = SFN1$
      SF$ = "C:\QB\MING\MSC\PDATA\" + SFN$ + ".dat"
      GOTO filename
   END IF
'
   npt% = iPmax% - 1
   INPUT "Input # points (Enter = Auto)"; pt%
   IF pt% > 0 THEN npt% = pt%
   fuel$ = "Methane"
   INPUT "Fuel (Enter = Methane)"; fuel1$
   IF fuel1$ <> "" THEN fuel$ = fuel1$
   dt = X(11) - X(10)
   PRINT "t(n+1) - t(n) = "; dt; " msec "; " dt =";
dpar!(4); "msec"
   INPUT "Okay ? (Enter = Yes/Continue, 2 = No/Stop)"; ok3%
```

```
     IF ok3% <> 0 THEN STOP
     REDIM com$(6), d!(npt%, 2), par!(11), par$(11), col1$(2),
col2$(2)
     FOR i = 1 TO npt%
          d!(i, 1) = X(i)               'time in msec
          d!(i, 2) = Y(i)               'P in kPa
     NEXT i
     com$(1) = "RECORDING THE EXPERIMENTAL PRESSURE TRACE"
     com$(2) = "DSK TING " + DATE$ + " AT " + TIME$
     com$(3) = "DATA ACQUIRED BY 4ChPlt.BAS"
     com$(4) = "FILENAME = " + SF$
     com$(5) = "Fuel = " + fuel$
     com$(6) = ""
     par!(1) = dpar!(1): par$(1) = " FREQUENCY (Hz) "
     par!(2) = dpar!(2): par$(2) = " Gain "
     par!(3)  =  dpar!(3):  par$(3)  =  " Reduction  Factor  for
Replay "
     par!(4) = dpar!(4): par$(4) = " dt (msec) "
     par!(5) = dpar!(5): par$(5) = " Equivalence Ratio "
     par!(6) = dpar!(6): par$(6) = " Plate Diameter (mm) "
     par!(7) = dpar!(7): par$(7) = " Plate Speed (m/s) "
     par!(8) = dpar!(8): par$(8) = " Spark Delay (ms) "
     par!(9)  =  dpar!(9):  par$(9)  =  " Turbulence  Intensity
(m/s) "
     par!(10) = Pmax: par$(10) = " Maximum Pressure (kPa) "

     par!(11) = tPmax: par$(11) = " Time at Pmax (ms) "
     col1$(1) = "  TIME": col2$(1) = "(msec)"
     col1$(2) = " PRESS": col2$(2) = "   kPa"
     CALL dwrite(npt%, 2, 6, 11, SF$, com$(), d!(), par!(),
par$(), col1$(), col2$())
     CLS : GOTO OPTIONS
'===============================================================
' Subroutine YESFILE
'
' File reading subroutine.
'
YESFILE:
     CALL DDIM(DNR%, DNC%, DNCOM%, dnpar%, DF$, TITLE$)
     REDIM   dcom$(DNCOM%),   dpar$(dnpar%),   dpar!(dnpar%),
dd!(DNR%, DNC%)
     REDIM DCOL1$(DNC%), DCOL2$(DNC%)
     CALL  DREAD(DNR%,  DNC%,  DNCOM%,  dnpar%,  DF$,  dcom$(),
dd!(), dpar!(), dpar$(), DCOL1$(), DCOL2$())
RETURN
'===============================================================
```

```
REM $STATIC
SUB Filter (i(), f(), n%, COV%)
'
'
' THIS IS A SIMPLE AVERAGING LOW PASS FILTER.
' It makes each point of F equal to an average of all points
within +/- cov%
' of the same point in the input array, I.
'
'
     IF COV% <= 0 THEN COV% = 4
     FOR i% = 1 TO n%
     SUM = i(i%)
         FOR j% = 1 TO COV%
             m% = i% - j%
             IF m% > 0 THEN
                 m = i(m%)
                 ELSE
                 m = i(1)
             END IF
             P% = i% + j%
             IF P% <= n% THEN
                 P = i(P%)
                 ELSE
                 P = 2 * i!(n%) - i(n% + n% - P%)
             END IF
             SUM = SUM + m + P
         NEXT j%
     f(i%) = SUM / (2 * COV% + 1)
     NEXT i%

END SUB
```

```
'       4CHPltT.bas
'       *********
'
'
'       Nov 1992          Ming Jiang

' This program is modified from DSK TING's 4CPlt.bas .
' It reads, plots and saves temperature-time data from '
digitization.
'
  DECLARE SUB Filter (i(), f(), n%, cov%)
      REM $INCLUDE: 'C:\QB\LIB\PLOTCOM.BAS'
      REM $INCLUDE: 'C:\QB\LIB\COLORCHC.BAS'
      REM $DYNAMIC

' Dimension some arrays.
      REDIM dcom$(20), dpar$(20), dpar!(20), dd!(20, 20)

' Set up the graphics screen.
      SCRN% = 9
' Get the data file.
      DFN$ = "1"
GETFILE:
      DF$ = "C:\QB\das16\data\" + DFN$ + ".dat"
      CLS : PRINT "Enter file name. (Enter= "; DF$; ")  >";
      INPUT DF1$
      IF DF1$ <> "" THEN
            DFN$ = DF1$
            GOTO GETFILE
      END IF
      GOSUB YESFILE
' Set # rows and # columns
      NROW% = DNR%
      NCOL% = DNC%
PLOTWHAT:
      CLS : INPUT "Enter column # for Y. (Enter=5) > "; coly

      IF coly = 0 THEN coly = 5
' Search the starting (SPARK) point
      FOR i = 2 TO DNR%
            IF dd!(i, 4) > 500 THEN
                  Ifirst = i + 4
                  GOTO STARTLOOP
            END IF
      NEXT i
STARTLOOP:
```

```
' Read Y and X data.
     n% = DNR% - Ifirst - 1
     REDIM X(n%), Y(n%)
     FOR i = 1 TO n%
          X(i) = dd!(i + Ifirst, 1) - dd!(Ifirst, 1)
          Y(i) = dd!(i + Ifirst, coly)
     NEXT i
' Filter Y(i) to smooth it out.
'
   REDIM XYF(n%)
   NUMFILT = 0
   NCOV% = 3
FILTER2:
   IF NUMFILT < 2 THEN
     CALL Filter(Y(), XYF(), n%, NCOV%)
     FOR i = 4 TO n%
        Y(i) = XYF(i)
     NEXT i
     NUMFILT = NUMFILT + 1
     NCOV% = NCOV% - 1
     GOTO FILTER2
   END IF

IF coly > 5 THEN GOTO Plotting
' **************Change to suit****************
' Convert temperature to V and then to DegreeC
IF coly < 3 THEN
          FOR i = 1 TO n%
               Y(i)  =  .001964  *  dd!(i  +  Ifirst,  coly)  -
.001677
          NEXT i
     ELSEIF coly = 5 THEN
          FOR i = 1 TO n%
               Y(i)  =  .0004945  *  dd!(i  +  Ifirst,  coly)  +
.00192
          NEXT i
     ELSE
          FOR i = 1 TO n%
               Y(i) = .004945 * dd!(i + Ifirst, coly) - .04835

          NEXT i
     END IF

   PRINT "Initial Temperature (V) = "; Y(5); " V"
   INPUT "Okay ? (Enter = Yes/Continue, 2 = No/Stop)"; ok%
   IF ok% <> 0 THEN STOP
```

```
    PRINT "Y(degC) = a * Y(V) + b"
    INPUT "a ="; a!                        'a=102.4 for 5*.dat only,
 else a=103.637
    INPUT "Initial temperature (degC) = "; Tinit!
    b! = Tinit! - a! * (Y(4) + Y(5) + Y(6)) / 3
    PRINT "b ="; b!
    FOR i = 1 TO n%
        Y(i) = a! * Y(i) + b!
    NEXT i
    Pjk = (Y(4) + Y(5)) / 2!
    PRINT "Initial pressure (kPa) = "; Pjk; " kPa"
    INPUT "Okay ? (Enter = Yes/Continue, 2 = No/Stop)"; ok2%

    IF ok2% <> 0 THEN STOP
 ' Maximum temperature rise (degC)
    IF coly = 5 THEN
      Tmax = 0
      FOR i = 2 TO n% - 3
          Yavg = (Y(i - 1) + Y(i) + Y(i + 1)) / 3!
          IF Yavg > Tmax THEN
            Tmax = Yavg           ' Tmax (degC)
            tTmax = X(i)          ' Time at Tmax (ms)
            iTmax% = i
          END IF
      NEXT i
    END IF
Plotting:
'----------------------------------------------------------------
' Data plotting section.
PLOTSECTION:
      XLB$ = "Time (msec)"
      YLB$ = "T (degC)"
      SCREEN 0: WIDTH 80: COLOR 15, 1
      CLS : PRINT "Plotting"
      INDAX% = 0: XSUB% = 0: YSUB% = 0
      CALL AXES(X(), Y(), n%, XSUB%, YSUB%, Xmn, Xmx, Xdv,
NXS%, Ymn, Ymx, Ydv, NYS%)
      Ymn = 10: Ydv = 5
      Xmn = 0!: Xdv = 10
'
LINETYPE:
      LIN% = 1
      CHAR% = 0
      CALL PINI(SCRN%, 1): c% = ngc%
      CALL YAXIS(Ymn, Ymx, Ydv, YSUB%, NYSUBD%, YLB$, Y2$, Y3$,
c%)
```

```
     CALL XAXIS(Xmn, Xmx, Xdv, XSUB%, NXSUBD%, XLB$, c%)
'
PLOTMORE:
     CALL LINPLT(X(), Y(), n%, CHAR%, 1, 6!, c%)
     LOCATE 3, 15: PRINT " File " + DF$
     LOCATE 5, 14: PRINT USING " Tmax =####.# degC"; Tmax
     LOCATE 5, 34: PRINT USING " at ###.## ms after spark";
tTmax
'-----------------------------------------------------------
' Finished plots, now what?
'
OPTIONS:
     LOCATE 1, 1
     INPUT " 0=hard copy, 1=quit, 2=restart, 3=change Y,
4=save >"; opt
     IF opt = 4 THEN GOTO SAVE
     IF opt = 3 THEN GOTO PLOTWHAT
     IF opt = 2 THEN GOTO GETFILE
     IF opt = 1 THEN SCREEN 0: COLOR 15, 1: CLS : END
     IF opt = 0 THEN CALL PHCOPY(xyz$)
'
SAVE:
     SFN$ = DFN$ + "T"
     SF$ = "C:\QB\ming\msc\tdata\" + SFN$ + ".dat"
filename:
     CLS : PRINT "ABOUT TO WRITE TO "; SF$
     INPUT "ENTER = GO ON, ELSE ENTER A NEW FILE NAME.>";
SFN1$
     IF SFN1$ <> "" THEN
          SFN$ = SFN1$
          SF$ = "C:\QB\ming\msc\tdata\" + SFN$ + ".dat"
          GOTO filename
     END IF
'
     npt% = iTmax% - 1
     INPUT "Input # points (Enter = Auto)"; pt%
     IF pt% > 0 THEN npt% = pt%
     fuel$ = "Methane"
     INPUT "Fuel (Enter = Methane)"; fuel1$
     IF fuel1$ <> "" THEN fuel$ = fuel1$

     REDIM com$(6), d!(npt%, 2), par!(11), par$(11), col1$(2),
col2$(2)
     dt = X(11) - X(10)
     PRINT "t(n+1) - t(n) = "; dt; " msec "; " dt =";
dpar!(4); "msec"
```

```
     INPUT "Okay ? (Enter = Yes/Continue, 2 = No/Stop)"; ok3%

     IF ok3% <> 0 THEN STOP
     FOR i = 1 TO npt%
         d!(i, 1) = X(i)                   'time in msec
         d!(i, 2) = Y(i)                   'T in degC
     NEXT i
     com$(1) = "RECORDING THE EXPERIMENTAL TEMPERATURE TRACE"

     com$(2) = "MING JIANG " + DATE$ + " AT " + TIME$
     com$(3) = "DATA ACQUIRED BY 4CPLT.BAS"
     com$(4) = "FILENAME = " + SF$
     com$(5) = "Fuel = " + fuel$
     com$(6) = ""
     par!(1) = dpar!(1): par$(1) = " FREQUENCY (Hz) "
     par!(2) = dpar!(2): par$(2) = " Gain "
     par!(3) = dpar!(3): par$(3) = " Reduction Factor for
Replay "
     par!(4) = dpar!(4): par$(4) = " dt (msec) "
     par!(5) = dpar!(5): par$(5) = " Equivalence Ratio "
     par!(6) = dpar!(6): par$(6) = " Plate Diameter (mm) "
     par!(7) = dpar!(7): par$(7) = " Plate Speed (m/s) "
     par!(8) = dpar!(8): par$(8) = " Spark Delay (ms) "
     par!(9) = dpar!(9): par$(9) = " Turbulence Intensity
(m/s) "
     par!(10) = Tmax: par$(10) = " Maximum Temperature (degC)
"
     par!(11) = tTmax: par$(11) = " Time at Tmax (ms) "
     col1$(1) = "  TIME": col2$(1) = "(msec)"
     col1$(2) = " TEMP ": col2$(2) = "   DegC"
     CALL DWRITE(npt%, 2, 6, 11, SF$, com$(), d!(), par!(),
par$(), col1$(), col2$())
     CLS : GOTO OPTIONS
'=====================================================================
' Subroutine YESFILE
'
' File reading subroutine.
'
YESFILE:
     CALL ddim(DWR%, DWC%, DWCOM%, dnpar%, DF$, TITLE$)
     REDIM  dcom$(DWCOM%),  dpar$(dnpar%),  dpar!(dnpar%),
dd!(DWR%, DWC%)
     REDIM DCOL1$(DWC%), DCOL2$(DWC%)
     CALL dread(DWR%, DWC%, DWCOM%, dnpar%, DF$, dcom$(),
dd!(), dpar!(), dpar$(), DCOL1$(), DCOL2$())
RETURN
```

```
'=====================================================================

REM $STATIC
SUB Filter (i(), f(), n%, cov%)
'
'
' THIS IS A SIMPLE AVERAGING LOW PASS FILTER.
' It makes each point of F equal to an average of all points
within +/- cov%
' of the same point in the input array, I.
'
'
     IF cov% <= 0 THEN cov% = 4
     FOR i% = 1 TO n%
     SUM = i(i%)
         FOR j% = 1 TO cov%
             m% = i% - j%
             IF m% > 0 THEN
                 m = i(m%)
                 ELSE
                 m = i(1)
             END IF
             P% = i% + j%
             IF P% <= n% THEN
                 P = i(P%)
                 ELSE
                 P = 2 * i!(n%) - i(n% + n% - P%)
             END IF
             SUM = SUM + m + P
         NEXT j%
     f(i%) = SUM / (2 * cov% + 1)
     NEXT i%

END SUB
```

PART 2

```
'      QGAUGEBM.BAS
'      ************
'      DEC 1992          MING JIANG

'This program calculates, plots and saves heatflux data from
'a measured temperature data file generated by 4CPltT.bas.
'Based on Leung's QSENSOR.BAS (Leung, 1991)

DECLARE SUB TRAPZ (IP, LP, w(), z(), O)
DECLARE SUB SLFILT (i(), F(), n%, cov%)
        REM $INCLUDE: 'C:\QB\LIB\PLOTCOM.BAS'
        REM $INCLUDE: 'C:\QB\LIB\COLORCHC.BAS'
        REM $DYNAMIC

' Dimension some arrays.
        REDIM dcom$(20), dpar$(20), dpar!(20), dD!(20, 20)
'Set up the graphics screen.
        SCRN% = 9
' Get the data file.
        DFN$ = "1"
GETFILE:
        DF$ = "C:\QB\ming\msc\tdata\" + DFN$ + ".dat"
        CLS : PRINT "Enter file name. (Enter= "; DF$; ")  >";

        INPUT DF1$
        IF DF1$ <> "" THEN
                        DFN$ = DF1$
                        GOTO GETFILE
        END IF
        GOSUB YESFILE

'this program uses the duhamel's integral method to calculate
'the surface heat flux (q) of the sensors based on the
'measured surface temperatures (ts) from the following files:

'          c:\qb\ming\msc\tdata\.Dat

           n% = DNR%
           REDIM TS(n%), TT(n%), X(n%), Y(n%), DTK(n%), dt(n%)

           REDIM Q(n%), z(n%), t(n%), SUMQ(n%), F(n%)

           FOR i = 1 TO DNR%
           t(i) = dD!(i, 1)
           TS(i) = dD!(i, 2)
           t(i) = t(i) / 1000      'convert t's unit to sec.
```

```
        TS(i) = TS(i)
        NEXT i

'the duhamel's integral method is done as follows:
'at each point in time i, if the number of time interval NI
'within the period from the beginning of ignition to i is less
'than 80, each time interval will be subdivided into ID
'divisions so that the total number of divisions within the
'period is 80. The temperatures at points between the time
'intervals are then linearly interpolated so that the heat
'flux at time i can be obtained by integrating the duhamel's
'function of temperature and time over the 80 divisions using
'the trapezoidal rule. If NI is greater than 80, no sub-
'division is required.

        FOR i = 1 TO n%
        NI = i - 1                    'number of interval.
            IF NI = 0 THEN
                Q(i) = 0!
            ELSE
                IF (NI > 80) THEN ID = 1
'ID=interval divisions
                IF (NI <= 80) THEN ID = INT(80 / NI)
                i1 = NI * ID + 1
                n = 1
                FOR J = 1 TO i1 STEP ID
                    X(J) = t(n)
                    Y(J) = TS(n)
                    n = n + 1
                NEXT J
                FOR J = 1 TO i1 STEP ID
                    IF (J = i1) THEN TT(J) = 0!
                    IF (J = i1) THEN GOTO 312
                    K1 = J
                    K2 = J + ID - 1
                    FOR K = K1 TO K2
    X(K) = (X(J + ID) - X(J)) * (K - J) / (ID) + X(J)
    Y(K) = (Y(J + ID) - Y(J)) * (K - J) / (ID) + Y(J)
    TT(K) = (TS(i) - Y(K)) / (t(i) - X(K)) ^ 1.5
    DTK(K) = (X(J + ID) - X(J)) / ID
                    NEXT K
                NEXT J

100         CALL TRAPZ(1, i1, DTK(), TT(), OQ)

                SQRKPC! = 1390
```

```
                    Q(i) = (SQRKPC! / 1.772) * (OQ / 2! +
(TS(i) - TS(1)) / t(i) ^ .5)
                    dt(i - 1) = t(i) - t(i - 1)
               END IF
          NEXT i

' Filter Q(i) to smooth it out.
'
     REDIM F(n%)
     NUMFILT = 0
     NCOV% = 5
FILTER2:
     IF NUMFILT < 2 THEN
          CALL SLFILT(Q(), F(), n%, NCOV%)
          FOR i = 1 TO n%
               Q(i) = F(i)
          NEXT i
          NUMFILT = NUMFILT + 1
          NCOV% = NCOV% - 1
          GOTO FILTER2
     END IF

 'Read Y and X data.
          REDIM X(n%), Y(n%)
          FOR i = 1 TO n%
               X(i) = t(i) * 1000  'convert time's unit to ms.

               Y(i) = Q(i)
          NEXT i
          Qmax = 0
          FOR i = 2 TO n% - 3
          Yavg = (Y(i - 1) + Y(i) + Y(i + 1)) / 3!
          IF Yavg > Qmax THEN
          Qmax = Yavg                   'Qmax(W/M^2)
          tQmax = X(i)                  'Time at Qmax(ms)
          iQmax% = i
          END IF
          NEXT i
Plotting:
'------------------------------------------------------------
' Data plotting section.
PLOTSECTION:
       XLB$ = "Time (msec)"
       YLB$ = "Heat"
       Y2$ = "Flux"
       Y3$ = "(w/m^2)"
```

```
        SCREEN 0: WIDTH 80: COLOR 15, 1
        CLS : PRINT "Plotting"
        INDAX% = 0: XSUB% = 0: YSUB% = 0
        CALL AXES(X(), Y(), n%, XSUB%, YSUB%, Xmn, Xmx, Xdv,
NXS%, Ymn, Ymx, Ydv, NYS%)
        Ymn = 0!
        Xmn = 0!: Xdv = 100
'
LINETYPE:
        LIN% = 1
        CHAR% = 0
        CALL PINI(SCRN%, 1): c% = ngc%
        CALL YAXIS(Ymn, Ymx, Ydv, YSUB%, NYSUBD%, YLB$, Y2$,
Y3$, c%)
        CALL XAXIS(Xmn, Xmx, Xdv, XSUB%, NXSUBD%, XLB$, c%)
'
PLOTMORE:
        CALL LINPLT(X(), Y(), n%, CHAR%, 1, 6!, c%)
LOCATE 3, 15: PRINT " File " + DF$
LOCATE 5, 14: PRINT USING " Qmax = ######.# w/m^2"; Qmax
LOCATE 5, 38: PRINT USING " at ###.## ms after spark"; tQmax
'----------------------------------------------------------
' Finished plots, now what?
'
OPTIONS:
        LOCATE 1, 1
        INPUT " 0=hard copy, 1=quit, 2=restart, 4=save >"; opt

        IF opt = 4 THEN GOTO SAVE
'      IF opt = 3 THEN GOTO PLOTWHAT
        IF opt = 2 THEN GOTO GETFILE
        IF opt = 1 THEN SCREEN 0: COLOR 15, 1: CLS : END
        IF opt = 0 THEN CALL PHCOPY(xyz$)
'
SAVE:
           SFN$ = DFN$ + "Q"
           SF$ = "C:\QB\MING\MSC\QDATA\" + SFN$ + ".dat"
filename:
           CLS : PRINT "ABOUT TO WRITE TO "; SF$
           INPUT "ENTER = GO ON, ELSE ENTER A NEW FILE NAME.>";
SFN1$
           IF SFN1$ <> "" THEN
                      SFN$ = SFN1$
                      SF$ = "C:\QB\MING\MSC\QDATA\" + SFN$ +
".dat"
                      GOTO filename
```

```
            END IF
'
            npt% = n% - 1
            INPUT "Input # points (Enter = Auto)"; pt%
            IF pt% > 0 THEN npt% = pt%
            fuel$ = "Methane"
            INPUT "Fuel (Enter = Methane)"; fuel1$
            IF fuel1$ <> "" THEN fuel$ = fuel1$
'       REM $DYNAMIC
            REDIM  com$(6),  d!(npt%,  2),  par!(11),  par$(11),
col1$(2), col2$(2)
            dt = X(11) - X(10)
      PRINT  "t(n+1)  -  t(n)  =  ";  dt;  "  msec  ";  "  dt  =";
dpar!(4); "msec"
      INPUT "Okay ? (Enter = Yes/Continue, 2 = No/Stop)"; ok3%
            IF ok3% <> 0 THEN STOP
            FOR i = 1 TO npt%
                        d!(i, 1) = X(i)              'time in msec

                        d!(i, 2) = Y(i)               'Q in W/M^2

            NEXT i
com$(1) = "RECORDING THE HEATFLUX TRACE"
com$(2) = "MING JIANG " + DATE$ + " AT " + TIME$
com$(3) = "DATA ACQUIRED BY QSENSORB.BAS"
com$(4) = "FILENAME = " + SF$
com$(5) = "Fuel = " + fuel$
com$(6) = ""
par!(1) = dpar!(1): par$(1) = " FREQUENCY (Hz) "
par!(2) = dpar!(2): par$(2) = " Gain "
par!(3) = dpar!(3): par$(3) = " Reduction Factor for Replay"
par!(4) = dpar!(4): par$(4) = " dt (msec) "
par!(5) = dpar!(5): par$(5) = " Equivalence Ratio "
par!(6) = dpar!(6): par$(6) = " Plate Diameter (mm) "
par!(7) = dpar!(7): par$(7) = " Plate Speed (m/s) "
par!(8) = dpar!(8): par$(8) = " Spark Delay (ms) "
par!(9) = dpar!(9): par$(9) = " Turbulence Intensity (m/s) "
par!(10) = Qmax: par$(10) = " Maximum HEATFLUX (W/M^2) "
par!(11) = tQmax: par$(11) = " Time at Qmax (ms) "
col1$(1) = "  TIME": col2$(1) = "(msec)"
col1$(2) = " HETFLX": col2$(2) = "   W/M^2"
CALL dwrite(npt%, 2, 6, 11, SF$, com$(), d!(), par!(), par$(),
col1$(), col2$())
CLS : GOTO OPTIONS
END
'=============================================================
```

```
' Subroutine YESFILE
'
' File reading subroutine.
'
YESFILE:
       CALL DDIM(DNR%, DNC%, DNCOM%, dnpar%, DF$, title$)
       REDIM  dcom$(DNCOM%),  dpar$(dnpar%),  dpar!(dnpar%),
dD!(DNR%, DNC%)
       REDIM DCOL1$(DNC%), DCOL2$(DNC%)
       CALL DREAD(DNR%, DNC%, DNCOM%, dnpar%, DF$, dcom$(),
dD!(), dpar!(), dpar$(), DCOL1$(), DCOL2$())
RETURN
'============================================================

REM $STATIC
SUB SLFILT (i(), F(), n%, cov%)
'((((((((((((((((((((((((((((((((((((((((((((((((((((((((((((
'
' SUBROUTINE SLFILT IS A SIMPLE AVERAGING LOW PASS FILTER.
' It makes each point of F equal to an average of all points
within +/- cov%
' of the same point in the input array, I.
'
' The routine requires points on either side of the point
being calculated
' so at the start and end of the array, extra points must be
created.
' In creating these points, some assumptions are necessary and
the ones
' used are that the slope is zero at the start of the array
and constant
' at the end of the array.
' As the slope is assumed to be zero at the start of the
array, any required
' values before the first point are set equal to the first
point.
' At the end of the array, the slope is forced to be constant
by replacing
' values after the last point with values greater than the
last point by
' an amount equal to the difference between the last point and
a point the
' same distance prior to the last point.
'
     IF cov% <= 0 THEN cov% = 4
     FOR i% = 1 TO n%
```

```
     SUM = i(i%)
          FOR J% = 1 TO cov%
               m% = i% - J%
               IF m% > 0 THEN
                    m = i(m%)
                     ELSE
                    m = i(1)
               END IF
               P% = i% + J%
               IF P% <= n% THEN
                    P = i(P%)
                     ELSE
                    P = 2 * i!(n%) - i(n% + n% - P%)
               END IF
               SUM = SUM + m + P
          NEXT J%
     F(i%) = SUM / (2 * cov% + 1)
     NEXT i%

END SUB

'
SUB TRAPZ (IP, LP, w(), z(), O)
'    subroutine to perform numerical integration using
'    trapezoidal rule.  The function z is integrated from
'    IP (initial point) to LP (last point) with interval
'    equal to w.  The solution of integration is stored
'    in o

          O = 0!
          IF (IP = LP) THEN GOTO 4
          K2 = LP - 1
          FOR K = IP TO K2
            O = O + (z(K) + z(K + 1)) / 2 * w(K)
          NEXT K
1    END SUB
```

PART 3

```
DECLARE SUB dwrite (R%, c%, cm%, P%, F$, cm$(), dd!(), P!(),
P$(), C1$(), C2$())
DECLARE SUB PINI (SCRN%, bcol%)
DECLARE SUB XAXIS (XMIN!, XMAX!, XDIV!, a%, nsubd%, xlb$,
col%)
DECLARE SUB YAXIS (YMIN!, YMAX!, YDIV!, a%, nsubd%, ylb1$,
ylb2$, ylb3$, col%)
DECLARE SUB LINPLT (xdat!(), ydat!(), NPNTS%, char%, lin%,
siz!, col%)
DECLARE SUB inscrn (N%, cl%, T%(), P$(), L%(), d$(), il%(),
ic%(), i$(), i%(), R!(), d#(), F$)
DECLARE SUB EQCONST ()
DECLARE SUB FLAME (INDV!, HEAT!, work!, PE!, FCA!, FHA!, FMW!,
S!, TR!, T!, MWR!, MWP!, FLAG%)
DECLARE SUB PROPCOEFF ()
DECLARE SUB REACTPROP (stoic!, FCA!, FHA!, FMW!, mf!, moxy#,
mn2#, MWR!)

'    EBMBPR2.BAS
'    ***********
'                          MD CHECKEL
'25 NOVEMBER, 1988 was original BMBPR2.BAS program made from
prior BMBPRESS.
'11 may 89: updated to account for RECAL89 and more moderate
early filtering.
'26 may 89: simplified early filtering a little more (sparkfi-
x4).
'2 aug 89: fixed defaults for 2 and 3 atm runs (sparkfix4 and
input section)
'26 sep 89: fixed way it reads CEL equivalence ratios.
'12 Jul 91: fixed to use modified CMBSUB (fixed FLAME sub-
routine).---Ming
'18 Jul 91: made a iteration in the burnt gas compression work
part.---Ming
'26 Dec 92: data reading part being changed to read data file
generated by 4chpltP.bas.---Ming
'31 Jan 93: renamed with "E" to indicate only experimental
data being used.---Ming

' BMBPR2 is BMBPRESS.BAS modified to include propane or
methane explosions.
' Converted back from BMBPR5N on 23 November, 1988.
' Based on BOMB.BAS per Alun Thomas's BOMB.BAS with correc-
tions re units, etc
' Uses thermodynamic properties and methods as described in
' Rowland S. Benson, "Advanced Engineering Thermodynamics"
```

```
' Pergammon Press, 1977, 2nd Edition (eg pg 153, Appendix A)

' NOTE REGARDING UNITS! The basic thermodynamic property
' relations in CMBSUB give properties of single components in
' the units J/kmol.k. The way REACTPROP subroutine does
' mixtures is to consider 1 mole of fuel + the associated
' oxygen and nitrogen.  The property coefficients for mixtures
' are the sum of coefficients for components so the units for
' properties of mixtures are J/(1 kmol of fuel + associated
' air).k.
' Each (1 kmol of fuel) has several kmol of air (21% oxygen,
' 79% nitrogen) associated with it so to get J/kmol.k for the
' mixture, you would divide through by the number of (kmol of
' mixture) per (1 kmol of fuel).  This is calculated by
' REACTPROP and stored as variable "molR" in the common
' block (defined by CMBCOM.BAS).  Later, after combustion,
' molR moles of reactants turns to "molP" moles of products
' for the same (1 kmol of fuel).
' The way this works is that you are generally dealling with
' units of so many joules per kmol of fuel and its associated
' air.  That way, even when the number of moles changes from
' reactants to products, (molR to molP), you are still
' dealling with the same quantity of matter and can just match
' the number of J for a 1st law energy balance.
' The complication comes when you start dealling with work or
' heat transferred out of an element during combustion.  Now,
' you have an absolute energy loss which must be added into
' the J/(1 kmol of fuel + air) energy balance.  To do so, the
' absolute energy quantity has to be converted to an energy
' loss in J/(1 kmol of fuel + associated air)
' In BMBPR2, the following variables are important:
' vUdelt# = volume of the element just before it burns (m^3)
' Mhc = kmol of fuel in the currently burning element (kmol)
' molR = total kmol of reactants per 1 kmol of fuel
' Therefore, if you take an absolute energy loss,
' Q (J/element), you would convert it to the appropriate units
' by multiplying:
' Q ( J/(1 kmol fuel + ? air) ) = Q (J/element) / Mhc (kmol
' fuel /element)

' This program calculates fates of elements of lean
' propane-air mixtures at specified starting conditions,
' burning in a constant volume bomb, based on the recorded
' pressure trace from the bomb.
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
     REM $INCLUDE: 'c:\qb\ming\msc\cmbcom.bas'
```

```
      REM $INCLUDE: 'c:\qb\lib\plotcom.bas'
      REM $INCLUDE: 'c:\qb\lib\colorset.bas'
      REM $DYNAMIC
      REDIM ic(8, 7), i$(8), cc(6), cw(6), R(7), P(7), m#(6),
W(8)
      REDIM TIME!(1201), fuel$(2)

      REM $DYNAMIC
      REDIM Res(1201, 9)
      NPAR% = 18: NCOM% = 6: NC% = 9
      REDIM com$(NCOM%), Par!(NPAR%), Par$(NPAR%), C1$(NC%),
C2$(NC%)

      x% = 6
      REDIM d$(x%), T%(x%), P$(x%), lg%(x%), L%(x%), c%(x%)
      REDIM ip$(x%), ip%(x%), ip!(x%), ip#(x%)

'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
     VERDAT$ = "JAN, 1993"
                           'set up some basic constants
     rmol = 8314.3         'ideal gas constant in J/kmol.k
     PN = 101325  'standard atmosphere in Pa (for Go and So)
     CALL PROPCOEFF
     CALL EQCONST
     REM $INCLUDE: 'c:\qb\ming\msc\cmbfN-RP.bas'
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
' set up arrays and open a file to read from
' Read the experimental data file.
  EF$ = " 1 "
getrun:
     EFP$ = "C:\QB\ming\msc\pdata\" + EF$ + ".DAT"
     CLS : PRINT "Enter the experimental data file.( Enter=";
EFP$; ") >";
     INPUT ; EF2$
     IF EF2$ <> "" THEN
          EF$ = EF2$
          GOTO getrun
     END IF
'----------------------------------------------------------
' File reading routine.
'
RFILE:
     REDIM  ED!(20,  20),  EPR!(20),  EPR$(20),  ECM$(20),
ECL1$(20), ECL2$(20)
     CALL DDIM(NRR%, NCC%, NCM%, NPR%, EFP$, ETITLE$)
     REDIM ECM$(NCM%), EPR$(NPR%), EPR!(NPR%), ED(NRR%, NCC%)
```

```
      REDIM ECL1$(NCC%), ECL2$(NCC%)
'
      CALL DREAD(NRR%, NCC%, NCM%, NPR%, EFP$, ECM$(), ED(),
EPR!(), EPR$(), ECL1$(), ECL2$())
       N% = NRR% + 1
       REDIM pr!(N%), F!(N%), TIME!(N%)
       FOR i = 1 TO NRR%
       pr!(i) = ED(i, 2)
       pr!(i) = 1000 * pr!(i)
       TIME!(i) = ED(i, 1)
       NEXT i
'------------------------------------------------------------
'The maximum #points
     NP% = NRR%
     IF NP% > 1200 THEN NP% = 1200
'------------------------------------------------------------
        V# = .001882#    ' Bomb volume in m^3 (Alberta cube)

          L = .062
          fuel% = 2: PRINT : PRINT

' Pspk is pressure at time of spark (in kPa)
     Pspk! = pr!(1) / 1000


'plot the pressure trace.

YMAX = 700000: YMIN = 100000
YDIV = 10: NY% = 10
XMAX = 200: XMIN = 0
XDIV = 10: NXSUB = 5
      SCRN% = 9
     CALL PINI(SCRN%, 1)
     xloc = ngxc + 10
     CALL XAXIS(XMIN, XMAX, XDIV, 0, NXSUB%, "TIME /(ms)", 15)

     CALL YAXIS(YMIN, YMAX, YDIV, 0, NY%, "PRESSURE", " /(kPa)
", "", 15)
     CALL LINPLT(TIME!(), pr!(), NP%, 0, 2, 8, 2)
     LOCATE 1, 1: PRINT SPACE$(79); : LOCATE 1, 1
     INPUT "Enter (0=O.K., -ve=re-start >"; tend
     IF tend = 0 THEN GOTO 500

'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
' Enter initial conditions and number of volume elements to
work on
```

```
500   bomb$ = "EBMBPR2 EBMBPR2 EBMBPR2 EBMBPR2 EBMBPR2 EBMBPR2
EBMBPR2 "
      bomb$ = LEFT$(bomb$ + bomb$, 79)
      Tinit = 293.15      ' pre-combustion temperature in k
      P0# = pr!(1)        ' pre-combustion pressure in Pa
      equiv = EPR!(5)     ' equivalence ratio
      IF equiv > .9999 THEN equiv = .9999
      feul$ = "CH4"
INPUTSECTION:
      COLOR NFC%, NBC%: CLS : PRINT bomb$: PRINT
      PRINT  "BOMB  COMBUSTION  EFFECTS  CALCULATION  PROGRAM:
EBMBPR2"
      PRINT
      PRINT "MING version of "; VERDAT$; ", run at ";
      PRINT TIME$; " on "; DATE$
      P$(1) = "Enter volume of bomb in m3 (0=" + STR$(V#) + ")
>"
      d$(1) = STR$(V#): T%(1) = 3: lg%(1) = 9: L%(1) = 7: c%(1)
= 10
      P$(2) = "Enter initial temperature  (0=" + STR$(Tinit)
+ ") >"
      d$(2) = STR$(Tinit): T%(2) = 1: lg%(2) = 7: L%(2) = 9:
c%(2) = 10
      P$(3) = "Enter initial pressure in Pa (0=" + STR$(P0#)
+ ") >"
      d$(3) = STR$(P0#): T%(3) = 2: lg%(3) = 15: L%(3) = 11:
c%(3) = 10
      P$(4) = "Enter equivalence ratio (0<E<0.9999), (0=" +
STR$(equiv) + ") >"
      d$(4) = STR$(equiv): T%(4) = 1: lg%(4) = 7: L%(4) = 13:
c%(4) = 10
      Pmax = EPR!(10)
      P$(5) = "Enter maximum pressure to analyze, (0=" +
STR$(Pmax) + " kPa) >"
      d$(5) = STR$(Pmax): T%(5) = 1: lg%(5) = 5: L%(5) = 18:
c%(5) = 10
      P$(6) = "Enter FUEL code (1=propane, 2=methane; default="

      P$(6) = P$(6) + fuel$(fuel%) + ") >"
      d$(6) = STR$(fuel%): T%(6) = 0: lg%(6) = 3: L%(6) = 21:
c%(6) = 10
CALL inscrn(6, 1, T%(), P$(), lg%(), d$(), L%(), c%(), ip$(),
ip%(), ip!(), ip#(), fx$)
      CLS : PRINT bomb$: PRINT : PRINT "INPUT VALUES:": PRINT
      IF ip#(1) > 0 THEN V# = ip#(1)
      PRINT "Bomb Volume,                V#="; V#
```

```
      Rbomb = (.75 * V# / 3.141592654#) ^ (1! / 3!)
      IF ip!(2) > 0 THEN Tinit = ip!(2)
      PRINT "Initial Temperature,        T="; Tinit
      IF ip#(3) > 0 THEN P0# = ip#(3)
      PRINT "Initial Pressure,           P="; P0#
      IF ip!(4) > 0 AND ip!(4) < .99991 THEN equiv = ip!(4)
      IF fuel% = 1 THEN AFRSTOIC = 15.5797 ELSE AFRSTOIC =
17.12
      AFR = AFRSTOIC / equiv: stoic = equiv
      PRINT USING "    EQUIV=#.###, AFR=###.#"; equiv; AFR
      MAXP = EPR!(10)
      PRINT "maximum pressure to analyze is MAXP="; MAXP
      N = NP%: nb = NP%
'&&&&&&&&&&&&&&&&&&&&&&&
      GOSUB fuelsort
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
      PRINT
      PRINT "USE <Ctrl> <PrtSc> to get HARD OUTPUT ON THE
PRINTER"
      INPUT "then hit <Enter>=continue (-1=new run)"; JUNK
      IF JUNK = -1 THEN GOTO getrun
'
' print out headings
'
      PRINT bomb$
      PRINT : PRINT SPACE$(14);
      PRINT "BOMB COMBUSTION EFFECTS CALCULATION PROGRAM:
EBMBPR2"
      PRINT : PRINT SPACE$(8);
      PRINT "MING version of "; VERDAT$; ", run at ";
      PRINT TIME$; " on "; DATE$
      PRINT
      frm$ = SPACE$(10) + "V=.#########m^3, R=.#######m,
Pi=###.###kPa,"
      frm$ = frm$ + " Ti=###.##k"
      PRINT USING frm$; V#; Rbomb; P0#; Tinit
      PRINT
      PRINT SPACE$(20); "Fuel = "; i$(7);
      PRINT USING ", A/F=##.## (#.### equiv)"; AFR; equiv
      frm$ = " n    Pr/kPa   Tu/k      Tb/k      Tb1/k"
      frm$ = frm$ + "     r/mm      r/R      r0/R      m/M"
      frm2$ = "###:#####.## ####.## ####.## ####.## "
      frm2$ = frm2$ + "###.#### #.##### #.##### #.#########"
      PRINT : PRINT frm$: PRINT
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
' MAIN LOOP: SELECT ELEMENT FOR PROCESSING - will burn NB
```

```
elements or until pressure exceeds MAXP
' first, get reactant properties prior to combustion
CALL REACTPROP(stoic, FCA, FHA, FMW, mf, moxy#, mn2#, MWR)
     gmR = fngamR(Tinit)   ' specific heat ratio of reactants
     mass# = MWR * P0# * V# / Tinit / rmol   ' total mass in
cell (kg)
     mburnt = 0: Vburnte# = 0: flag1% = 0: Vue# = V#
     MAXP = MAXP * 1000: PE = P0#
     TR = Tinit
     Pmax = 0: tb1 = 0

     nb = NP%

tstart = TIMER
  SUMQ = 0
  SUMW = 0
  TOTALW = 0

FOR i% = 1 TO nb
     PI = PE          ' Pi is pressure and Tlast is temperature
     Tlast = TR       ' of Reactants after last element burned.
                       ' in pascals and kelvin.

     IF pr!(i%) <= PI THEN
          vUdelt# = 0    ' cancel calculations if there is no
          vBdelt# = 0     ' pressure rise - assume no
          ve# = 0        ' combustion takes place and skip to
          T = 0           ' next pressure data point.
          GOTO converg
     ELSEIF pr!(i%) > MAXP THEN    ' or if the pressure rise
          nb = i% - 1     ' takes us past the maximum pressure
          GOTO gettend     ' to analyze, we can quit
     END IF
     PE = pr!(i%)
     PE! = PE          ' CHECK: is this the first pressure rise?
     ' if so, set flag1% which determines whether we have a
     ' previous result to use for interpolation
     IF flag1% = 0 AND PE > P0# THEN flag1% = 1
'BBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBB
' BURNT GAS COMPRESSION WORK:
' if there are previously burned elements, calculate the '
volume of each before and after compression to new pressure,
' PE. Then calculate the work done to compress each one and
' add it to the work sum done by the burning element.
     Vburnti# = Vburnte#  ' previous burnt volume (m^3 for all
elements)
```

```
      Vburnte# = 0
      Wburnt = 0          ' we start at i%>2 because there is no
                          ' combustion at i%=1 so the first
                          ' time we could have previously burned
                          ' gas elements is when i%=3

      IF i% > 2 THEN
        FOR J = 2 TO i% - 1
'vbi# is the volume of element J before compression.
'vbe# is the volume of element J after compression.
'Wbj is the compression work  of the Jth element.
'res(J,6) is volume of element J after combustion.
'res(J,2) is the pressure after combustion of element J.
'res(J,9) is the GAMMA of burned gas mixture.


        vbi# = Res(J, 6) * (Res(J, 2) / PI) ^ (1 / Res(J, 9))

        vbe# = Res(J, 6) * (Res(J, 2) / PE) ^ (1 / Res(J, 9))

        Wbj = (PE * vbe# - PI * vbi#) / (1 - Res(J, 9))
        Vburnte# = Vburnte# + vbe#
        Wburnt = Wburnt + Wbj
        NEXT J
        END IF
        Wburnt = -Wburnt


'BBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBB
endburnt:
'UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU
Tlast = TR      ' mixture at pressure Pi are stored here.
' Guess new TR (temp of reactants) based on Pressure rise and
' assumption of constant specific heats
     TR = Tlast * ((PE / PI) ^ ((gmR - 1) / gmR))
     gmR = fngamR(TR)      '   evaluate GAMMAreact at this Tr

'UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU
' Estimate the volume of gas burning to raise pressure from
PI to PE
' vUdelt# is the volume of the burning element before combus-
tion (Tlast,PI)
' vUdelt# will be iterated until we get the right amount.  The
' iteration loops back to the CALCVOLUMES label.
          vUdelt# = V# * (PE - PI) / (stoic * 6 * PI)
          flagV% = 0                  ' flagV%=0 indicates V is
```

```
first guess

CALCVOLUMES:
' Mhc is # of kmol of fuel in burning element
          Mhc = PI * vUdelt# / rmol / Tlast / molR
' Vui# is volume of the remaining unburnt mixture before
' combustion but excluding the burning element
          Vui# = V# - Vburnti# - vUdelt#    'in m^3
' Vue# is volume of unburnt mixture after this element burns
          Vue# = Vui# * (PI / PE) ^ (1 / gmR)    'in m^3
' Wu is work done on the unburnt mixture, (in absolute joules)

          Wu = (PE * Vue# - PI * Vui#) / (1 - gmR)
          Wu = -Wu
' total W ON previously burnt and unburnt is Wu+Wburnt in J.
' sum these up and convert to CMBSUB units of J/(1 kmol.fuel
' + associated air)
          SUMW = (Wburnt + Wu) / Mhc
' use subroutine FLAME to find the flame temperature of the
' burning element knowing its starting conditions and work
' output.

CALL FLAME(1!, 0!, SUMW!, PE, FCA, FHA, FMW, stoic, Tlast, T,
MWR, MWP, FL%)

 'calculate the volume this element would have if it burned
to temperature T at pressure PE. (molP) is number of moles of
products)
          vBdelt# = vUdelt# * PI / PE * T / Tlast * molP /
molR

' compare this with volume left over from unburned gas and
' previously burned elements at this pressure, PE.
          erv# = Vburnte# + vBdelt# + Vue# - V#
' if the error is greater than .001% then make a new estimate
' of burning volume & return to try again.
          IF ABS(erv#) > vUdelt# * .000001# THEN
          IF flagV% > 0 THEN
               VUD3# = (vUdelt# * ERVL# - Vud1# * erv#)
               VUD3# = VUD3# / (ERVL# - erv#)
               Vud1# = vUdelt#: vUdelt# = VUD3#: flagV% =
flagV% + 1
                    ELSE
               Vud1# = vUdelt#    '  otherwise change to a
               flagV% = 1         '  multiple of initial guess
               IF erv# > 0 THEN
```

```
                         vUdelt# = Vudl# / 1.1
                    ELSE
                         vUdelt# = Vudl# * 1.1
                    END IF
               END IF

' Having established new estimate for BURNT VOLUME after
' combustion, record current volume error. Go back to
' re-calculate the composition and temperature with the new
' volume estimate.
          ERVL# = erv#
          GOTO CALCVOLUMES
          END IF
'
' Once you make it past this END IF, you have estimated the
' correct volume burning to raise the pressure from PI to PE
' and have evaluated the state of the unburned and previously
' burned gases at PE.
'VVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVV
' CALCULATION OF VOLUMES HAVING CONVERGED, CALCULATE A FEW
' OTHER QUANTITIES STORE RESULTS OF COMBUSTION OF ELEMENT I%
' INTO THE RESULT ARRAY, RES

converg:
       MDELTA = vUdelt# * PI / rmol / Tlast * MWR
       mburnt = mburnt + MDELTA
       Vburnte# = Vburnte# + vBdelt#
       Res(i%, 1) = TIME(i%)  ' TIME in ms
       Res(i%, 2) = pr!(i%)    'pressure after combustion of
                               'element
'RR=relative radius of flame after element burns (assuming a
spherical flame and bomb)
       rr = ((Vburnte#) / V#) ^ (1 / 3)
       Res(i%, 3) = rr       ' RR is relative radius of flame
                             ' vs bomb radius
       mM = mburnt / mass# ' mM=mass fraction burned
       Res(i%, 4) = mM       ' mM is mass fraction burned
       Res(i%, 5) = vUdelt# 'VUDELT is volume of element
                         'before combustion
       Res(i%, 6) = vBdelt# 'Vbdelt is volume of element after
                            'combustion
       Res(i%, 7) = T       'T is temperature of element after
                            'combustion
       Res(i%, 8) = TR       'TR is unburned gas temperature
                             'after combustion
```

```
       IF T > 0 THEN
          Res(i%, 9) = fngamP(T)              ' GAMMA of burned gas
                                               ' mixture
               ELSE
          Res(i%, 9) = fngamR(T)
               END IF
       IF flag1% = 1 THEN
               tb0 = T: pb0 = PE    'conditions of first
               gammap0 = fngamP(T)  'element to burn are
                                'recorded here
               flag1% = -1
       ELSEIF flag1% = -1 THEN      'calculate TEMP OF FIRST
                                    'ELEMENT now
          tb1 = tb0 * (PE / pb0) ^ ((gammap0 - 1) / gammap0)

               END IF
      r0r = mM ^ (1 / 3!)     ' ROR=radius of this element at
                              ' spark time
      rmm = rr * Rbomb * 1000

      PRINT USING frm2$; i%; pr!(i%) / 1000; TR; T; tb1; rmm;
rr; r0r; mM
      IF PE > Pmax THEN Pmax = PE

     NEXT i%
' end of main loop
gettend:
     timend = TIMER         ' note how long it all took.
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
' CALCULATE THE FINAL TEMPERATURE OF EACH ELEMENT AFTER NB '
ELEMENTS HAVE BURNED AND THE PRESSURE HAS RISEN TO Pmax
     FOR i% = 1 TO nb
      IF Res(i%, 5) > 0 THEN
      g = Res(i%, 9)
      t1 = Res(i%, 8) * (Pmax / Res(i%, 2)) ^ ((g - 1) / g)
      g2 = fngamP(t1)
      g = (g + g2) * .5
      Res(i%, 9) = Res(i%, 8) * (Pmax / Res(i%, 2)) ^ ((g -
1) / g)
      END IF
      Res(i%, 2) = Res(i%, 2) / 1000!'convert from Pa to kPa
     NEXT i%
'&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
     PRINT : tdiff = timend - tstart: mins = INT((timend -
tstart) / 60)
     PRINT "elapsed time is"; mins; " min,"; tdiff - 60 *
```

```
mins; " sec"
     PRINT
' warble to notify its done
     FOR J = 1 TO 5
                freq = 200 + 200 * J
                SOUND freq, 1
                NEXT J


' store the calculated quantities in an output file
     Res$ = EF$ + "NH"
     F$ = "C:\QB\ming\MSc\Bmdata\" + Res$ + ".dat"
'
NAMEFILE:
     PRINT "ABOUT TO WRITE TO "; F$
     INPUT "Enter = go on, else enter a new file. >"; JUNK$

     IF JUNK$ <> "" THEN
          F$ = "C:\QB\ming\msc\bmdata\" + JUNK$ + ".dat"
          PRINT
          GOTO NAMEFILE
     END IF
'
     INPUT "Fuel ="; FL$
     com$(1) = "Output of bomb pressure trace analysis."
     com$(2) = "Ming version of " + VERDAT$ + ", run at " +
TIME$
     com$(2) = com$(2) + " on " + DATE$
     com$(3) = "FILE = " + F$
     com$(4) = "FUEL = " + FL$
     com$(5) = ""
'
     Par!(1) = EPR!(1): Par$(1) = " FREQUENCY (Hz) "
     Par!(2) = EPR!(2): Par$(2) = " Gain "
     Par!(3) = EPR!(3): Par$(3) = " Reduction Factor for
Replay "
     Par!(4) = EPR!(4): Par$(4) = " dt (msec) "
     Par!(5) = EPR!(5): Par$(5) = " Equivalence Ratio "
     Par!(6) = EPR!(6): Par$(6) = " Plate Diameter (mm) "
     Par!(7) = EPR!(7): Par$(7) = " Plate Speed (m/s) "
     Par!(8) = EPR!(8): Par$(8) = " Spark Delay (ms) "
     Par!(9) = EPR!(9): Par$(9) = " Turbulence Intensity (m/s)
"
     Par!(10) = EPR!(10): Par$(10) = " Maximum Pressure (kPa)
"
     Par!(11) = EPR!(11): Par$(11) = " Time at Pmax (ms) "
```

```
     Par!(12) = pr!(1) / 1000: Par$(12) = " kPa Initial
Pressure "
     Par!(13) = Tinit: Par$(13) = " K Initial Temperature "

     Par!(14) = Rbomb: Par$(14) = " m bomb radius "
     Par!(15) = mass#: Par$(15) = " kg mixture mass "
     Par!(16) = V#: Par$(16) = " m^3 cell volume "
'
     C1$(1) = " TIME  ": C2$(1) = " ms  "
     C1$(2) = " PRESS ": C2$(2) = " kPA "
     C1$(3) = "RADIUSb": C2$(3) = " /R  "
     C1$(4) = " MASSb ": C2$(4) = " /M  "
     C1$(5) = "dVOLunb": C2$(5) = " m^3 "
     C1$(6) = "dVOLbrn": C2$(6) = " m^3 "
     C1$(7) = " T burn": C2$(7) = "deg k"
     C1$(8) = " Tunb ": C2$(8) = "deg k"
     C1$(9) = "T final": C2$(9) = "deg k"
     NR% = nb
      CALL dwrite(NR%, NC%, NCOM%, NPAR%, F$, com$(), Res(),
Par!(), Par$(), C1$(), C2$())
'
'                                            finish off program
     PRINT
     CLS
     INPUT "enter 0 to read another run, 1 to quit >"; IND
     IF IND = 0 THEN GOTO getrun
END
'===============================================================
' fuelsort is a subroutine which switches the correct fuel
' into the property array and sets up correct fuel molecule
' variables
'
fuelsort:
     IF ip%(6) > 0 AND ip%(6) < 3 THEN fuel% = ip%(6)
IF fuel% = 1 THEN
'fuel=propane
     FCA = 3               'fuel has FCA carbon atoms per atom
     FHA = 8                'fuel has FHA hydrogens per atom
     FMW = 44.09            'fuel molar mass in kg/kgmol
          ELSE
'fuel =methane
     FCA = 1
     FHA = 4
     FMW = 16.043
          END IF
```

```
' if we don't have the current fuel in I$(7) then swap with
i$(8)
     IF fuel$(fuel%) <> i$(7) THEN
          FOR i = 1 TO 6
               temp = ic(7, i): ic(7, i) = ic(8, i): ic(8, i)
= temp
               NEXT i
          temp$ = i$(7): i$(7) = i$(8): i$(8) = temp$
          END IF
     PRINT "Fuel is " + i$(7) + " and coefficients are:"
     FOR i = 1 TO 7: PRINT SPACE$(10); ic(7, i): NEXT i
RETURN
```

PART 4

```
'       htCoef.bas
'       **********
'
'
'       March 1993          MING JIANG
'
' This program calculates,plots and saves heat transfer '
coefficient data.

DECLARE SUB FILTER (i!(), f!(), n%, COV%)

        REM $INCLUDE: 'C:\QB\LIB\PLOTCOM.BAS'
        REM $INCLUDE: 'C:\QB\LIB\COLORCHC.BAS'
        REM $DYNAMIC

' Dimension some arrays.
        REDIM dcom$(20), dpar$(20), dpar!(20), dd!(20, 20)

' Set up the graphics screen.
        SCRN% = 9
'UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU
' Get the unburnt gases temperature data file.
        DFN$ = "1"
GETFILE:
        DF$ = "C:\QB\ming\msc\bmDATA\" + DFN$ + ".dat"
        CLS : PRINT "Enter file name. (Enter= "; DF$; ")  >";
        INPUT DF1$
        IF DF1$ <> "" THEN
                DFN$ = DF1$
                GOTO GETFILE
        END IF
        GOSUB YESFILE
        REDIM Tu!(DNR%), TuTIME!(DNR%), r!(DNR%)
        FOR i = 1 TO DNR%
        Tu!(i) = dd!(i, 8)
        TuTIME!(i) = dd!(i, 1)
        r!(i) = dd!(i, 3)
        NEXT i
'TTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTT
' Read the experimental wall temperature data file.
   EF$ = " 1 "
GETRUN:
        EFP$ = "C:\QB\ming\msc\tdata\" + EF$ + ".DAT"
        CLS : PRINT "Enter the experimental pressure data file.(
Enter="; EFP$; ") >";
        INPUT ; EF2$
```

```
     IF EF2$ <> "" THEN
          EF$ = EF2$
          GOTO GETRUN
     END IF
'-----------------------------------------------------------
' File reading routine.
'
RFILE:
     REDIM  ED!(20,  20),  EPR!(20),  EPR$(20),  ECM$(20),
ECL1$(20), ECL2$(20)
     CALL DDIM(NRR%, NCC%, NCM%, NPR%, EFP$, ETITLE$)
     REDIM ECM$(NCM%), EPR$(NPR%), EPR!(NPR%), ED(NRR%, NCC%)

     REDIM ECL1$(NCC%), ECL2$(NCC%)
'
     CALL DREAD(NRR%, NCC%, NCM%, NPR%, EFP$, ECM$(), ED(),
EPR!(), EPR$(), ECL1$(), ECL2$())
      n% = NRR% + 10
      REDIM Tw!(n%), f!(n%), TwTIME!(n%)
      FOR i = 1 TO NRR%
      Tw!(i) = ED(i, 2) + 273
      TwTIME!(i) = ED(i, 1)
      NEXT i
'QQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQ
' Read the experimental heatflux data file.
  QF$ = " 1 "
getf:
     QFP$ = "C:\QB\ming\msc\qdata\" + QF$ + ".DAT"
     CLS : PRINT "Enter the experimental heatflux data file.(
Enter="; QFP$; ") >";
     INPUT ; QF2$
     IF QF2$ <> "" THEN
          QF$ = QF2$
          GOTO getf
     END IF
'-----------------------------------------------------------
' File reading routine.
'
YFILE:
     REDIM  QD!(20,  20),  QPAR!(20),  QPAR$(20),  QCON$(20),
QCOL1$(20), QCOL2$(20)
     CALL DDIM(QNR%, QNC%, QNCON%, QNPAR%, QFP$, QTITLE$)
     REDIM   QCON$(QNCON%),   QPAR$(QNPAR%),   QPAR!(QNPAR%),
QD(QNR%, QNC%)
     REDIM QCOL1$(QNC%), QCOL2$(QNC%)
'
```

```
      CALL DREAD(QNR%, QNC%, QNCOM%, QNPAR%, QFP$, QCOM$(),
QD(), QPAR!(), QPAR$(), QCOL1$(), QCOL2$())
       n% = QNR% + 10
       REDIM q!(n%), f!(n%), QTIME!(n%)
       FOR i = 1 TO QNR%
       q!(i) = QD(i, 2)
       QTIME!(i) = QD(i, 1)
       NEXT i
'ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
      NP% = DNR%
      tQmax = QPAR!(11)
'calculate the heat transfer coefficient.
      REDIM h!(DNR%), TIME!(DNR%), hF!(DNR%)
      FOR i = 1 TO NP%

      TIME!(i) = QTIME!(i)
      h!(i) = q!(i) / (Tu!(i) - Tw!(i))
      IF TIME!(i) > tQmax THEN
      NP% = i - 1
      GOTO 100
      END IF

      NEXT i
' Filter h to smooth it out.
'
100  NUMFILT = 0
     NCOV% = 5
FILTER1:
     IF NUMFILT < 2 THEN
         CALL FILTER(h(), hF(), NP%, NCOV%)
         FOR i = 1 TO NP%
             h(i) = hF(i)
         NEXT i
         NUMFILT = NUMFILT + 1
         NCOV% = NCOV% - 1
         GOTO FILTER1
     END IF

' Read Y and X data.
     n% = NP%
     REDIM X(n%), Y(n%)
     FOR i = 1 TO n%
          X(i) = r(i)
          Y(i) = h(i)
     NEXT i
' Maximum heat transfer coefficient.
```

```
     hmax = 0
     FOR i = 2 TO n% - 3
        Yavg = (Y(i - 1) + Y(i) + Y(i + 1)) / 3!
        IF Yavg > hmax THEN
          hmax = Yavg                 ' hmax (w/m^2.K)
          thmax = X(i)                ' Time at hmax (ms)
          ihmax% = i
        END IF
     NEXT i
' Search For Keypoints
' *********************
'
' Input the required radius, then calculate the corresponding
parameters
     R1req = .7
     INPUT "Enter required radius. (Enter=.7)  >"; Rreq1
     IF Rreq1 > 0 THEN R1req = Rreq1
     R2req = .8
     INPUT "Enter required radius. (Enter=.8)  >"; Rreq1
     IF Rreq1 > 0 THEN R2req = Rreq1
'
     FOR i = 2 TO n%
         IF dd(i, 3) < R1req THEN I3 = i
         IF dd(i, 3) < R2req THEN I4 = i
     NEXT i
     T1req = dd(I3, 7)
     R1req = dd(I3, 3)
     Mb1 = dd(I3, 4)
     T2req = dd(I4, 7)
     R2req = dd(I4, 3)
     Mb2 = dd(I4, 4)
INPUT "Equation based on r/Rcell or P (Enter=r, 2=P)"; jk
IF jk = 2 THEN
     Pfirst = 125
     Plast = 200
     INPUT "Pfirst (kPa) = (Enter = 125 kPa)"; P1%
     IF P1% > 0 THEN Pfirst = P1%
     INPUT "Plast (kPa) = (Enter = 200 kPa)"; P2%
     IF P2% > 0 THEN Plast = P2%
ELSE Rfirst = .6
     Rlast = .95
     INPUT "starting Rb/Rcell (Enter=0.6)"; Rd1
     IF Rd1 > 0 THEN Rfirst = Rd1
     INPUT "ending Rb/Rcell (Enter=0.95)"; Rd2
     IF Rd2 > 0 THEN Rlast = Rd2
```

```
END IF
'PPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPP
PLOTTING:
' Data plotting section.
PLOTSECTION:
     XLB$ = "r/Rcell"
     YLB$ = "h (w/m^2.K)"
     SCREEN 0: WIDTH 80: COLOR 15, 1
     CLS : PRINT "Plotting"
     INDAX% = 0: XSUB% = 0: YSUB% = 0
CALL AXES(X(), Y(), n%, XSUB%, YSUB%, Xmn, Xmx, Xdv, NXS%,
Ymn, Ymx, Ydv, NYS%)
     Ymn = 0: Ydv = 100
     Xmn = 0!: Xdv = .1
'
LINETYPE:
     LIN% = 1
     CHAR% = 0
     CALL PINI(SCRN%, 1): c% = ngc%
     CALL YAXIS(Ymn, Ymx, Ydv, YSUB%, NYSUBD%, YLB$, y2$, Y3$,
c%)
     CALL XAXIS(Xmn, Xmx, Xdv, XSUB%, NXSUBD%, XLB$, c%)
'
PLOTMORE:
     CALL LINPLT(X(), Y(), n%, CHAR%, 1, 6!, c%)
' Equation Of Line
IF jk > 1 THEN
' Equation from Pfirst to Plast
     FOR i = 1 TO n%
          IF dd(i, 2) > Pfirst THEN f% = i - 1: GOTO foundlast

     NEXT i
foundlast:
     FOR i = 1 TO n%
          IF dd(i, 2) > Plast THEN l% = i - 1: GOTO foundfirst

     NEXT i
ELSE
' Equation from Rfirst to Rlast
     FOR i = 1 TO n%
      IF dd(i, 3) > Rfirst THEN f% = i - 1: GOTO fdl
     NEXT i
fdl:
     FOR i = 1 TO n%
      IF dd(i, 3) > Rlast THEN l% = i - 1: GOTO foundfirst
     NEXT i
```

```
END IF
foundfirst:
     n% = l% - f% - 1
     FOR i = 1 TO n%
          Y(i) = Y(i + f%)
          X(i) = X(i + f%)
     NEXT i
     REDIM lsc(2)
     CALL ls(n%, 0, X(), Y(), lsc(), r)
     eqn$ = " h = " + STR$(lsc(1)) + " + X * " + STR$(lsc(2))

     LOCATE 3, 14: PRINT eqn$
     LOCATE 3, 55: PRINT " r = "; r
     ystart = lsc(1) + lsc(2) * Rfirst
     y1 = lsc(1) + lsc(2) * R1req
     y2 = lsc(1) + lsc(2) * R2req
     yend = lsc(1) + lsc(2) * Rlast
CALL pplot(Rfirst, ystart, 0, c%): CALL NGPOINT(5, 6!, c% -
2)
CALL pplot(Rlast, yend, 1, 12): CALL NGPOINT(5, 6!, c% + 1)
     LOCATE 5, 40: PRINT USING "h=##.##W/M^2.K"; y1
     LOCATE 5, 14: PRINT USING ", Rflame/Rcell=#.##"; R1req
     LOCATE 6, 40: PRINT USING "h=##.##W/M^2.K"; y2
     LOCATE 6, 14: PRINT USING ", Rflame/Rcell=#.##"; R2req
CALL pplot(R1req, y1, 0, c%): CALL NGPOINT(6, 6!, c% - 1)
CALL pplot(R2req, y2, 0, c%): CALL NGPOINT(6, 6!, c% - 1)
'---------------------------------------------------------------
' Finished plots, now what?
'
OPTIONS:
     LOCATE 1, 1
     INPUT " 0=hard copy, 1=quit, 2=restart, 3=save >"; opt

     IF opt = 3 THEN GOTO SAVE
     IF opt = 2 THEN GOTO GETFILE
     IF opt = 1 THEN SCREEN 0: COLOR 15, 1: CLS : END
     IF opt = 0 THEN CALL PHCOPY(xyz$)
'
SAVE:
     SFN$ = QF$
     SF$ = "C:\QB\NING\MSC\HDATA\" + SFN$ + ".dat"
filename:
     CLS : PRINT "ABOUT TO WRITE TO "; SF$
     INPUT "ENTER = GO ON, ELSE ENTER A NEW FILE NAME.>";
SFN1$
     IF SFN1$ <> "" THEN
```

```
        SFN$ = SFN1$
        SF$ = "C:\QB\ming\msc\HDATA\" + SFN$ + ".dat"
        GOTO filename
    END IF
'
    npt% = n% - 1
    INPUT "Input # points (Enter = Auto)"; pt%
    IF pt% > 0 THEN npt% = pt%
    fuel$ = "Methane"
    INPUT "Fuel (Enter = Methane)"; fuel1$
    IF fuel1$ <> "" THEN fuel$ = fuel1$

    REDIM com$(6), d!(npt%, 2), par!(11), par$(11), col1$(2),
col2$(2)
    dt = X(11) - X(10)
    PRINT "t(n+1) - t(n) = "; dt; " msec "; " dt =";
dpar!(4); "msec"
    INPUT "Okay ? (Enter = Yes/Continue, 2 = No/Stop)"; ok3%

    IF ok3% <> 0 THEN STOP
    FOR i = 1 TO npt%
        d!(i, 1) = X(i)                'time in msec
        d!(i, 2) = Y(i)                'h in w/m^2.K
    NEXT i
    com$(1) = "HEAT TRANSFER COEFFICIENTS BEFORE THE FLAME
TOUCHES CELL WALLS"
    com$(2) = "M.JIANG " + DATE$ + " AT " + TIME$
    com$(3) = "DATA ACQUIRED BY HTCOEF.BAS"
    com$(4) = "FILENAME = " + SF$
    com$(5) = "Fuel = " + fuel$
    com$(6) = ""
    par!(1) = dpar!(1): par$(1) = " FREQUENCY (Hz) "
    par!(2) = dpar!(2): par$(2) = " Gain "
    par!(3) = dpar!(3): par$(3) = " Reduction Factor for
Replay "
    par!(4) = dpar!(4): par$(4) = " dt (msec) "
    par!(5) = dpar!(5): par$(5) = " Equivalence Ratio "
    par!(6) = dpar!(6): par$(6) = " Plate Diameter (mm) "
    par!(7) = dpar!(7): par$(7) = " Plate Speed (m/s) "
    par!(8) = dpar!(8): par$(8) = " Spark Delay (ms) "
    par!(9) = dpar!(9): par$(9) = " Turbulence Intensity
(m/s) "
    par!(10) = hmax: par$(10) = " Maximum h (w/m^2.K) "
    par!(11) = thmax: par$(11) = " Time at hmax (ms) "
    col1$(1) = "  TIME": col2$(1) = "(msec)"
    col1$(2) = " HTCOEF": col2$(2) = "   w/m^2.K"
```

```
     CALL DWRITE(npt%, 2, 6, 11, SF$, com$(), d!(), par!(),
par$(), col1$(), col2$())
     CLS : GOTO OPTIONS
'=================================================================
' Subroutine YESFILE
'
' File reading subroutine.
'
YESFILE:
     CALL DDIM(DNR%, DNC%, DNCOM%, dnpar%, DF$, TITLE$)
     REDIM  dcom$(DNCOM%),  dpar$(dnpar%),  dpar!(dnpar%),
dd!(DNR%, DNC%)
     REDIM DCOL1$(DNC%), DCOL2$(DNC%)
     CALL  DREAD(DNR%,  DNC%,  DNCOM%,  dnpar%,  DF$,  dcom$(),
dd!(), dpar!(), dpar$(), DCOL1$(), DCOL2$())
RETURN
'=================================================================
REM $STATIC
SUB FILTER (i(), f(), n%, COV%)
'
'
' THIS IS A SIMPLE AVERAGING LOW PASS FILTER.
' It makes each point of F equal to an average of all points
within +/- cov%
' of the same point in the input array, I.
'
'
     IF COV% <= 0 THEN COV% = 4
     FOR i% = 1 TO n%
     SUM = i(i%)
         FOR J% = 1 TO COV%
             m% = i% - J%
             IF m% > 0 THEN
                 m = i(m%)
                 ELSE
                 m = i(1)
             END IF
             P% = i% + J%
             IF P% <= n% THEN
                 P = i(P%)
                 ELSE
                 P = 2 * i!(n%) - i(n% + n% - P%)
             END IF
```

```
               SUM = SUM + m + P
            NEXT J%
         f(i%) = SUM / (2 * COV% + 1)
         NEXT i%

   END SUB

   SUB REDUCEBY4 (tfact, itpmax%, pr!(), TIME!())
   ' This routine compresses the pressure array to 1/4 of its
   original length
   ' with each point being an average of the 5 previously
   covered.
         J% = 1
         TIME!(1) = 0
         pr!(J%) = (pr!(1) + pr!(2)) * .5
         tfact = tfact * 4!
         FOR i% = 2 TO itpmax% + 5 STEP 4
               J% = J% + 1
               SUM = 0
               FOR K% = 1 TO 4
                     SUM = SUM + pr!(i% + K%)
                     NEXT K%
               pr!(J%) = SUM / 4
               TIME!(J%) = tfact * (J% - 1)
               NEXT i%
         itpmax% = J%

   END SUB
```

APPENDIX B

Representative experimental measurements were presented in Chapter 4. The remaining measurements are presented in this appendix to provide a complete record of the data from this study.

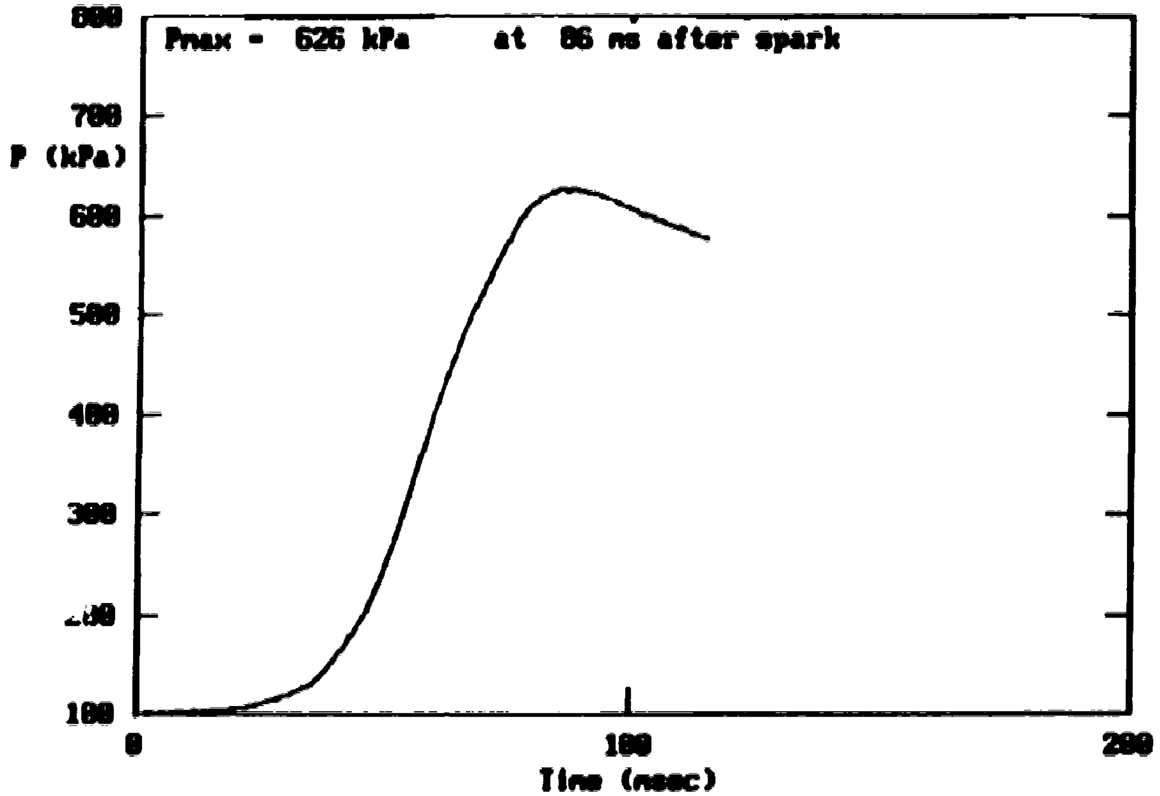

Figure B-1 Pressure variation with time; laminar combustion; P_{init} = 1 atm; equivalence ratio 0.85.

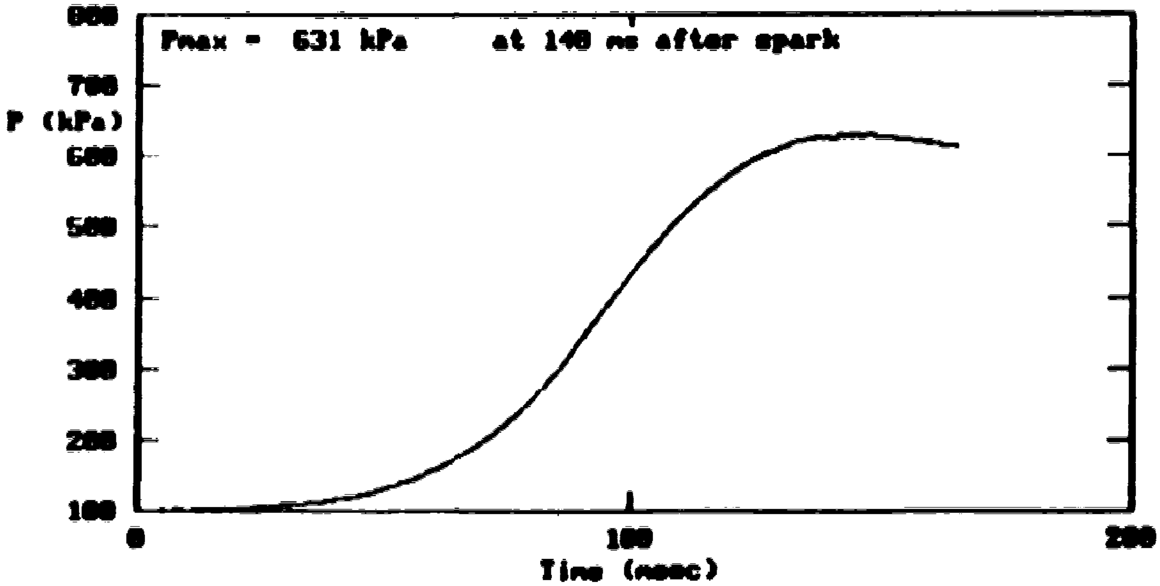

Figure B-2 Pressure variation with time; laminar combustion; P_{init} = 1 atm; equivalence ratio 0.75.

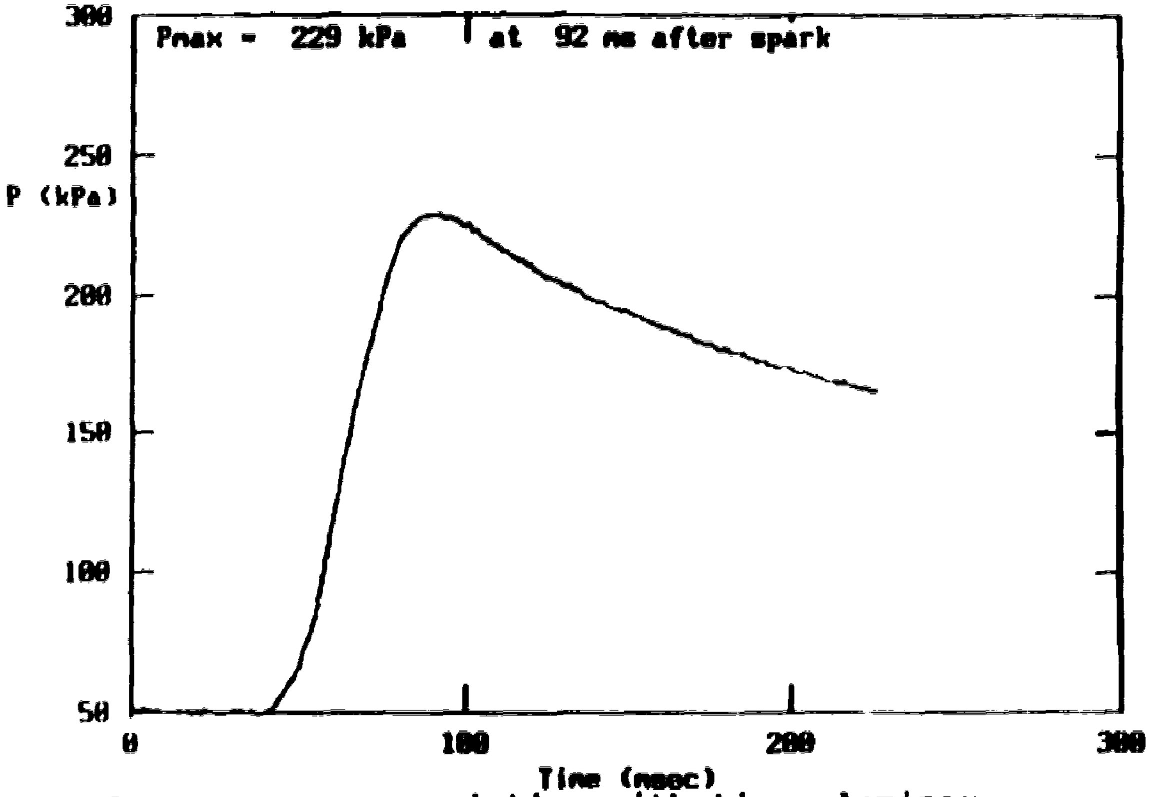

Figure B-3 Pressure variation with time; laminar combustion; P_{init} = 0.5 atm; equivalence ratio 0.75.

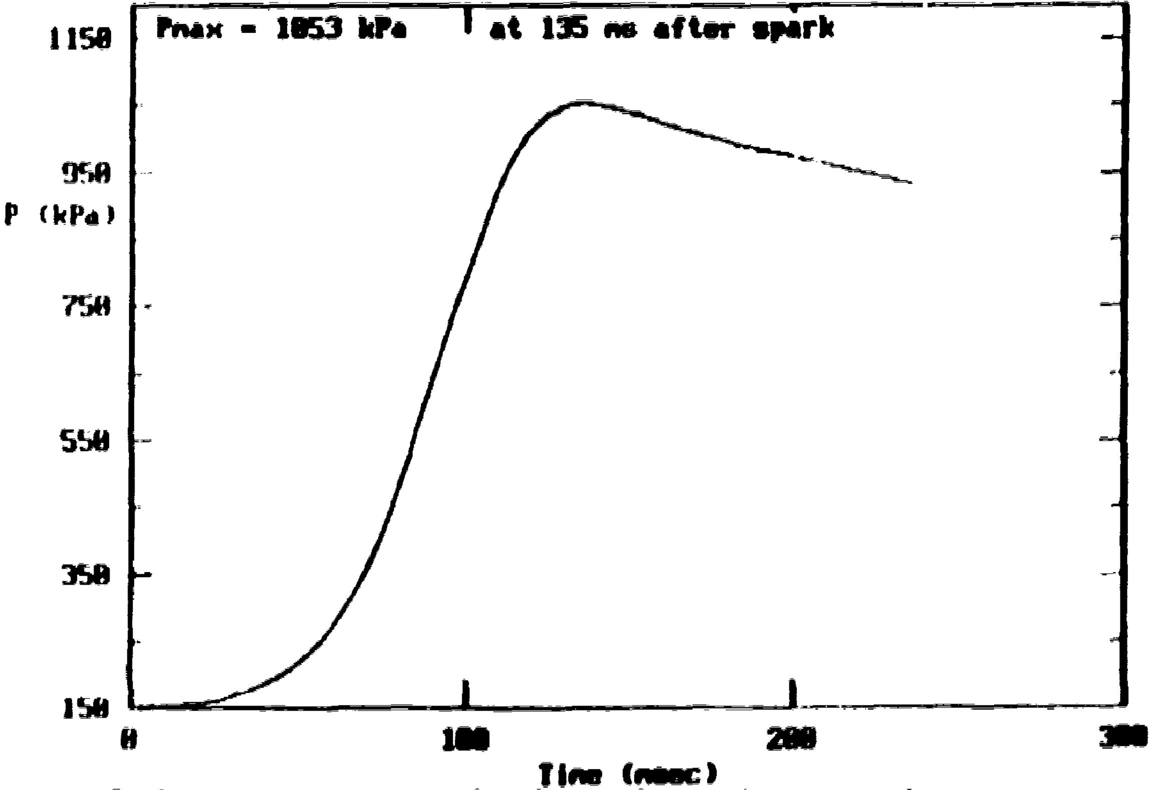

Figure B-4 Pressure variation with time; laminar combustion; P_{init} = 1.5 atm; equivalence ratio 0.75.

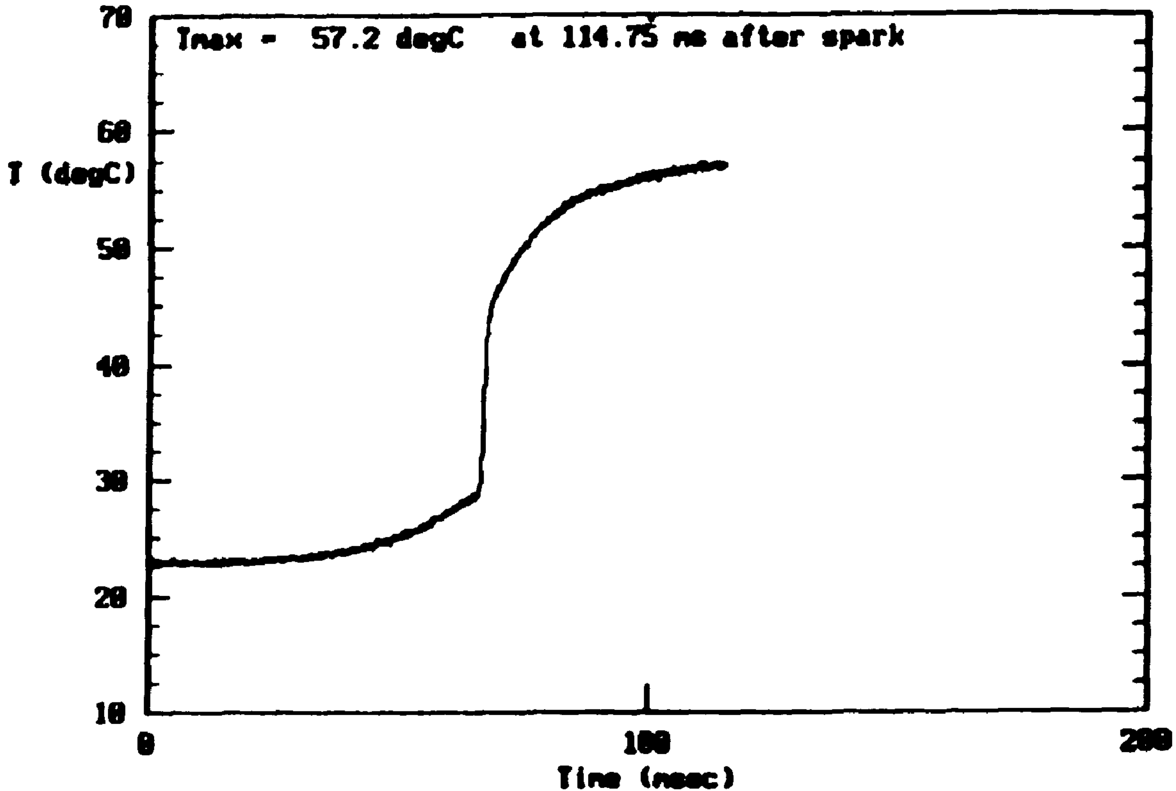

Figure B-5 Wall temperature variation with time; laminar combustion; P_{init} = 1 atm; equivalence ratio 0.85.

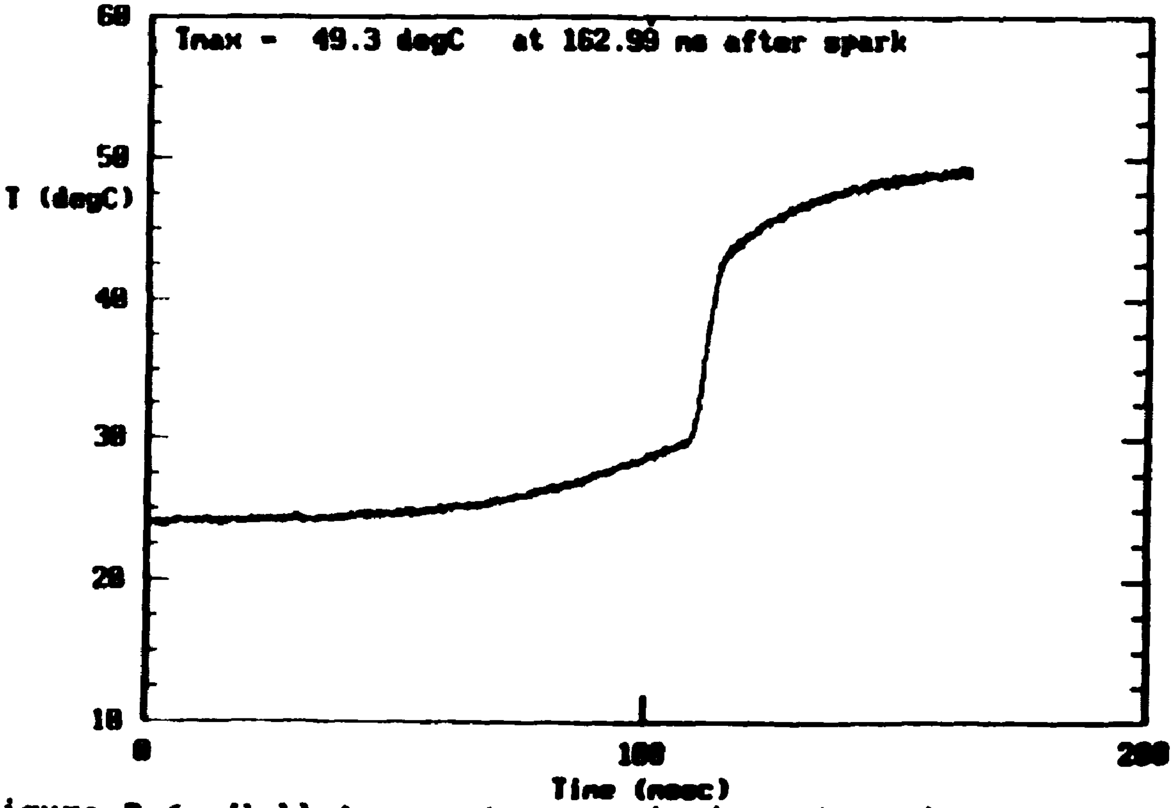

Figure B-6 Wall temperature variation with time; laminar combustion; P_{init} = 1 atm; equivalence ratio 0.75.

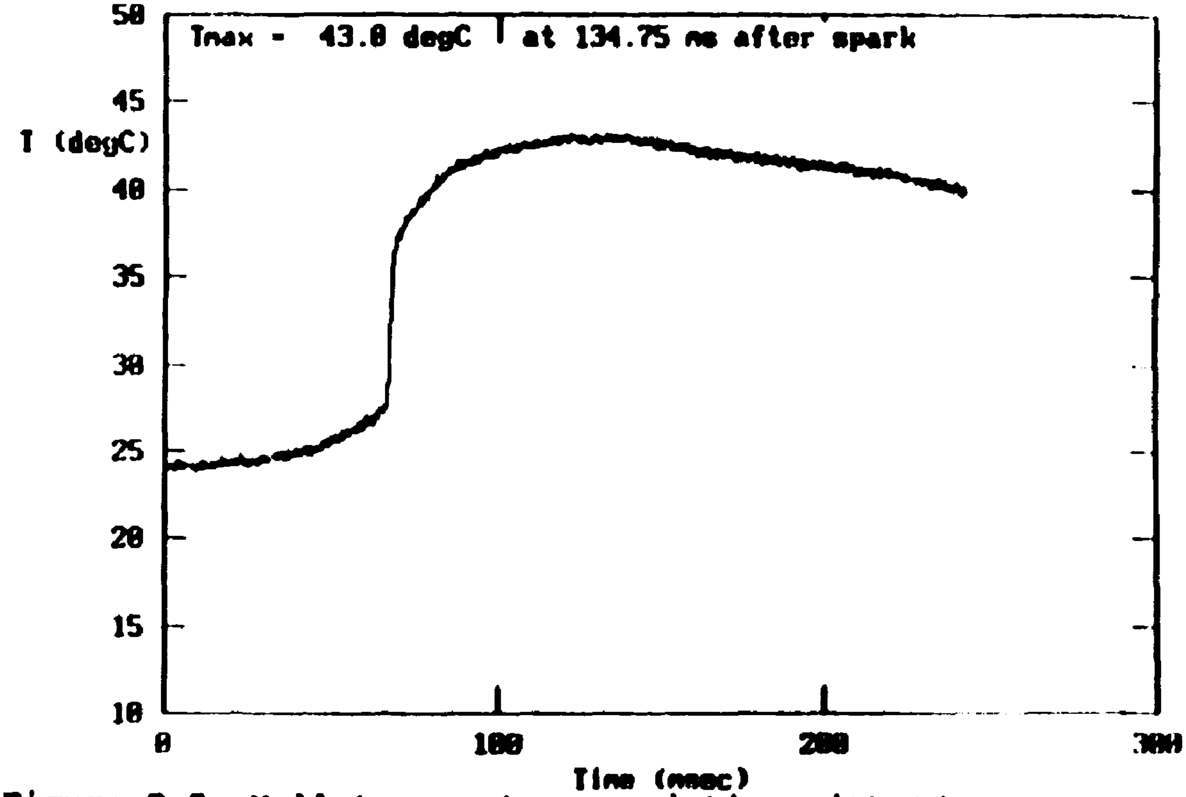

Figure B-7 Wall temperature variation with time; laminar combustion; P_{init} = 0.5 atm; equivalence ratio 0.75.

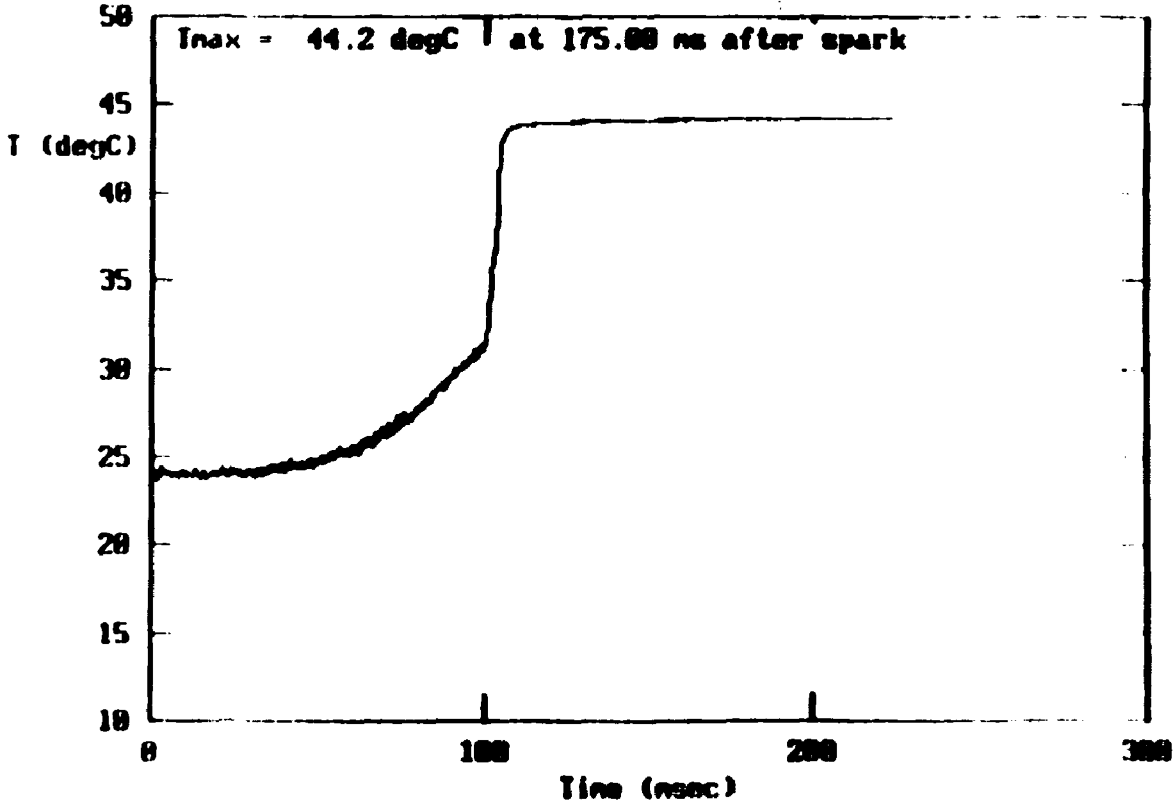

Figure B-8 Wall temperature variation with time; laminar combustion; P_{init} = 1.5 atm; equivalence ratio 0.75.

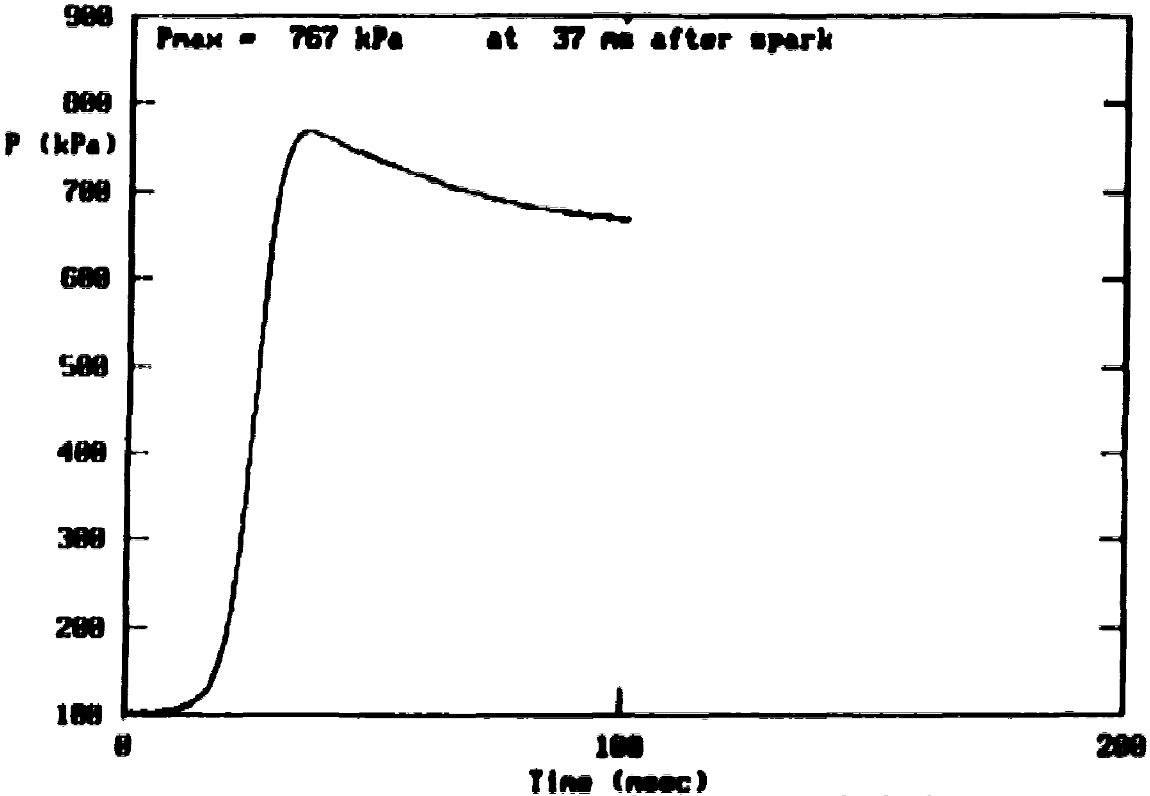

Figure B-9 Pressure variation with time; initial turbulence intensity 0.5 m/s; P_{init} = 1 atm; equivalence ratio 1.0.

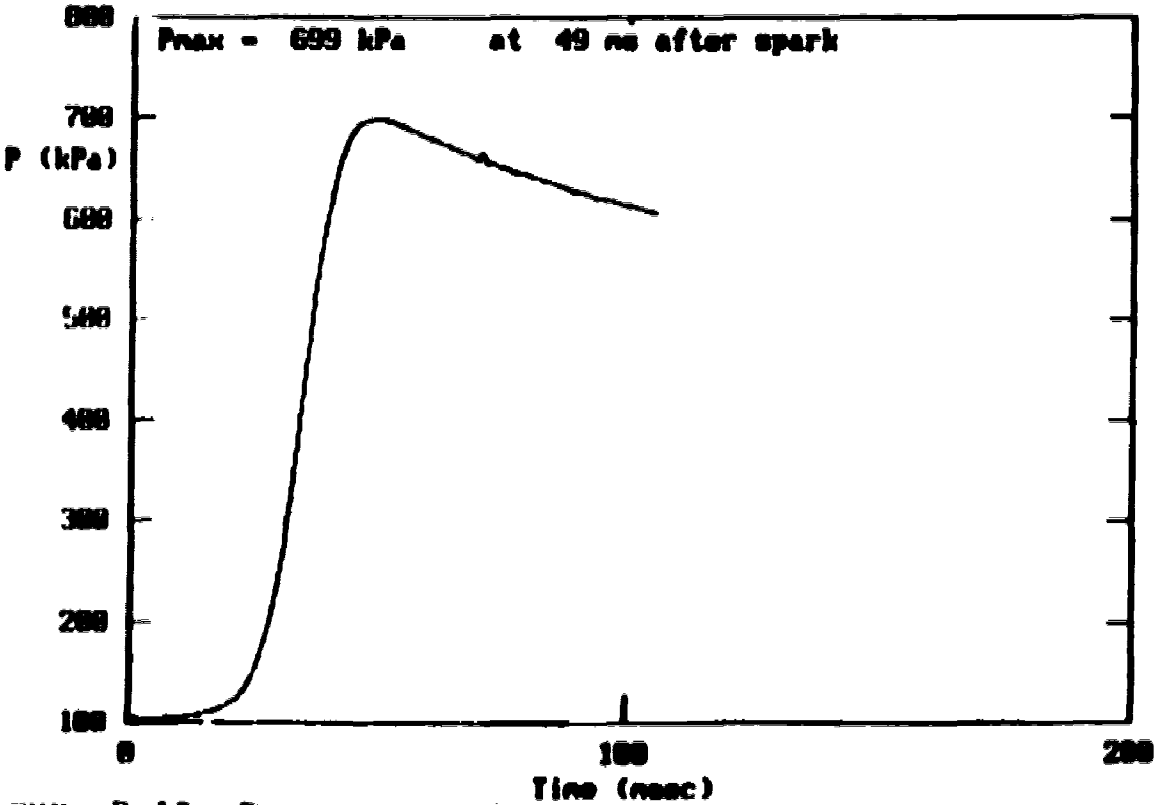

Figure B-10 Pressure variation with time; initial turbulence intensity 0.5 m/s; P_{init} = 1 atm; equivalence ratio 0.85.

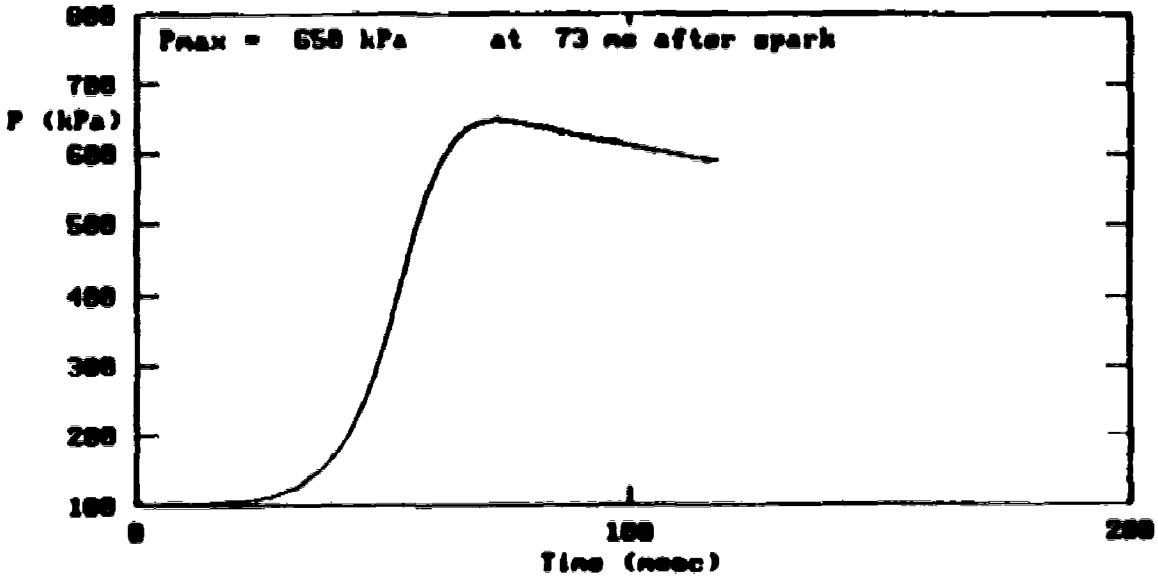

Figure B-11 Pressure variation with time; initial turbulence intensity 0.5 m/s; P_{init} = 1 atm; equivalence ratio 0.75.

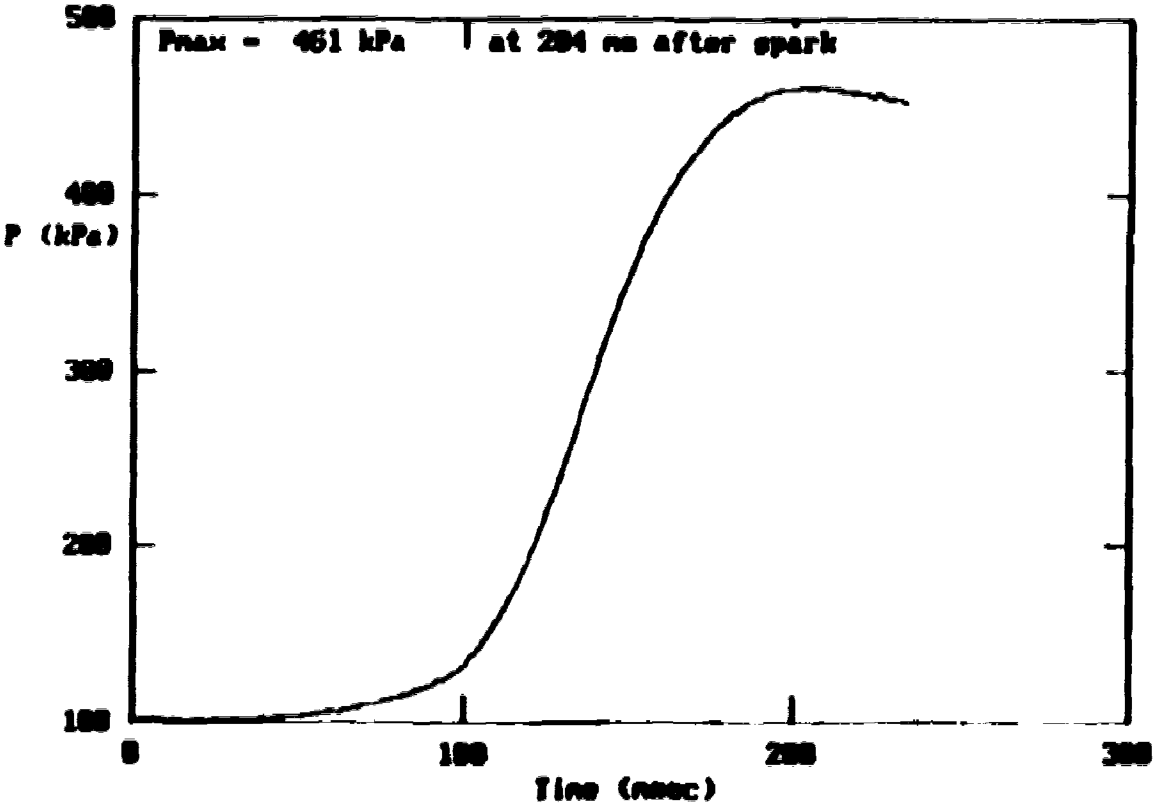

Figure B-12 Pressure variation with time; initial turbulence intensity 0.5 m/s; P_{init} = 1 atm; equivalence ratio 0.6.

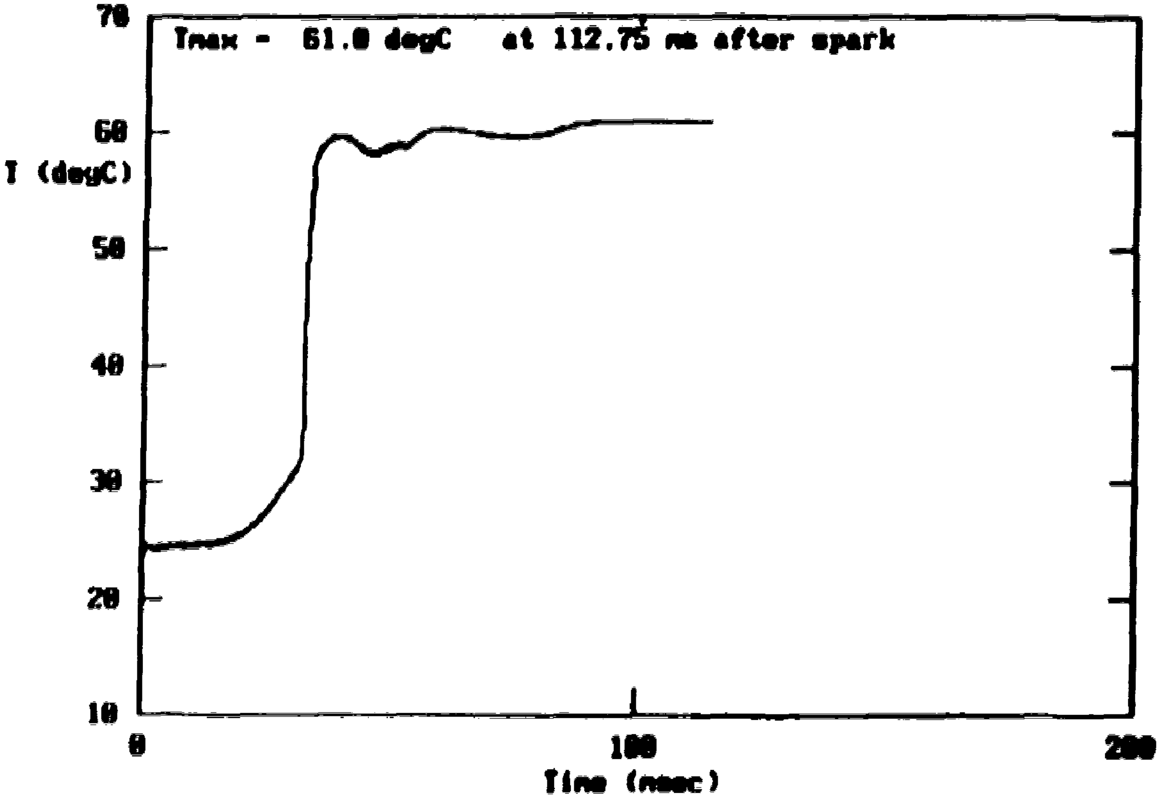

Figure B-13 Wall temperature variation with time; initial turbulence intensity 0.5 m/s; P_{init} = 1 atm; equivalence ratio 1.0.

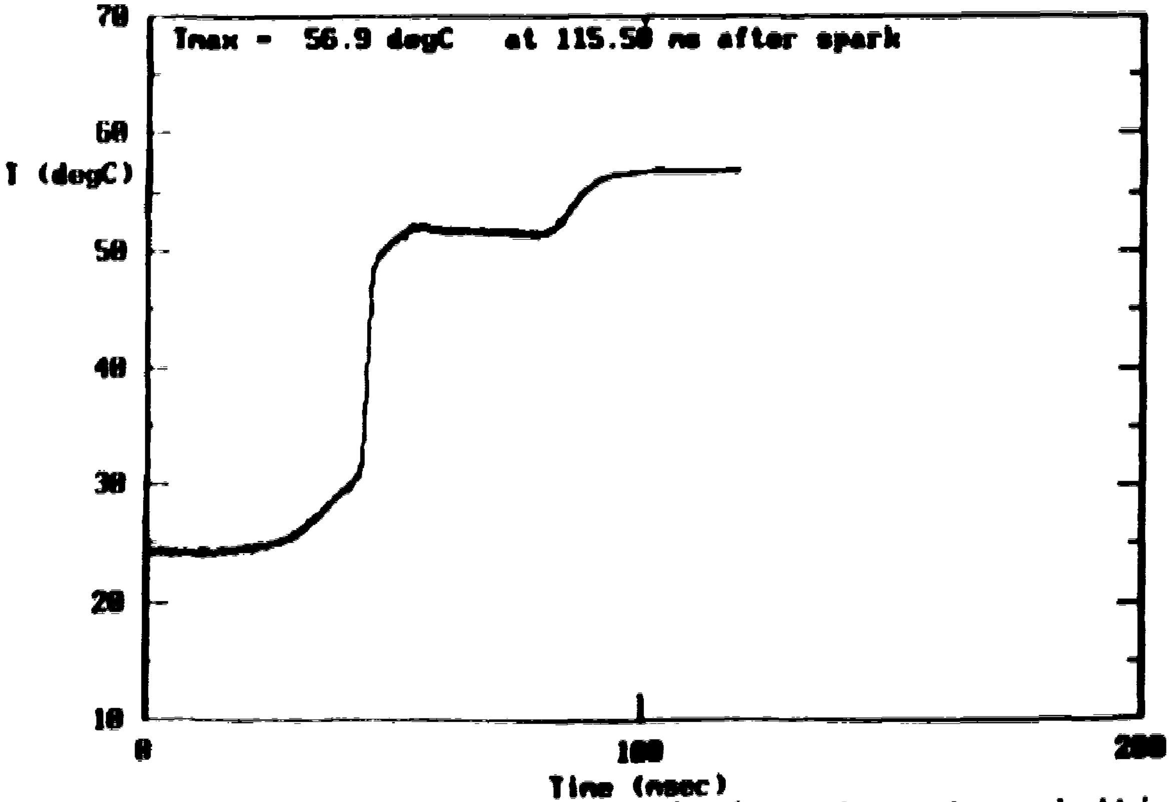

Figure B-14 Wall temperature variation with time; initial turbulence intensity 0.5 m/s; P_{init} = 1 atm; equivalence ratio 0.85.

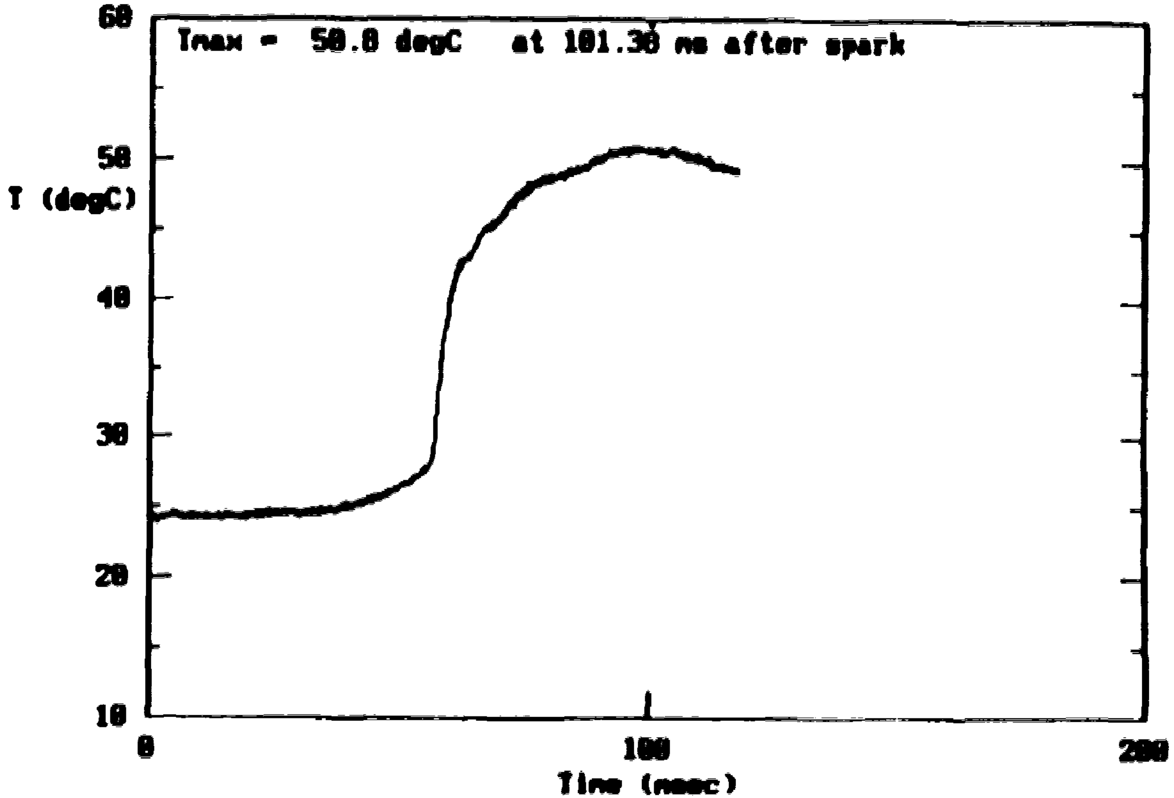

Figure B-15 Wall temperature variation with time; initial turbulence intensity 0.5 m/s; P_{init} = 1 atm; equivalence ratio 0.75.

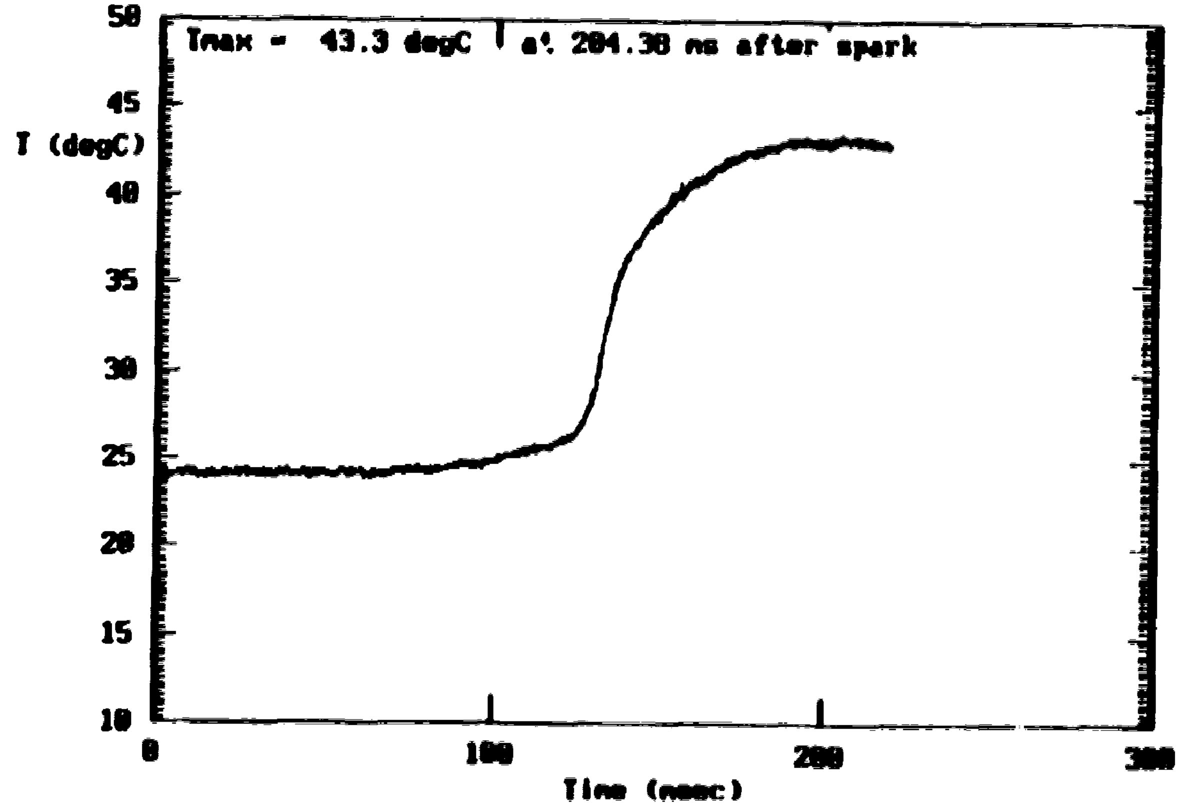

Figure B-16 Wall temperature variation with time; initial turbulence intensity 0.5 m/s; P_{init} 1 atm; equivalence ratio 0.6.

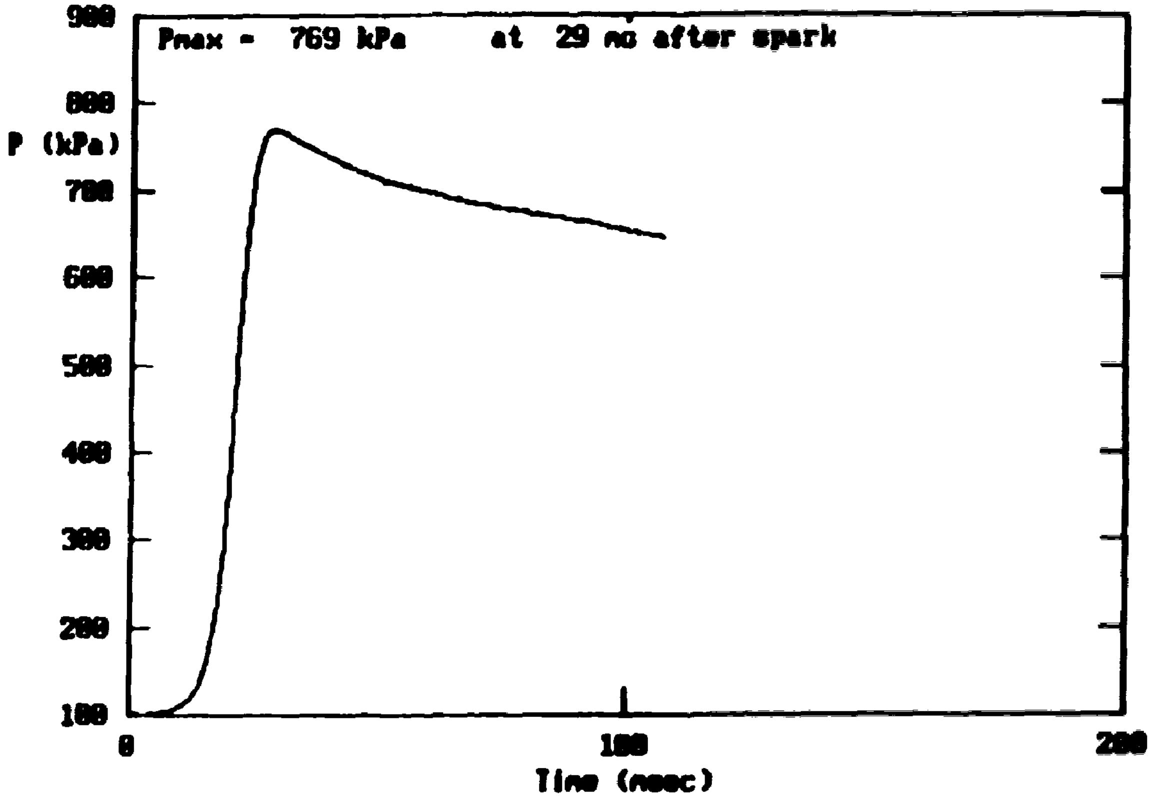

Figure B-17 Pressure variation with time; initial turbulence intensity 1.0 m/s; P_{init} = 1 atm; equivalence ratio 1.0.

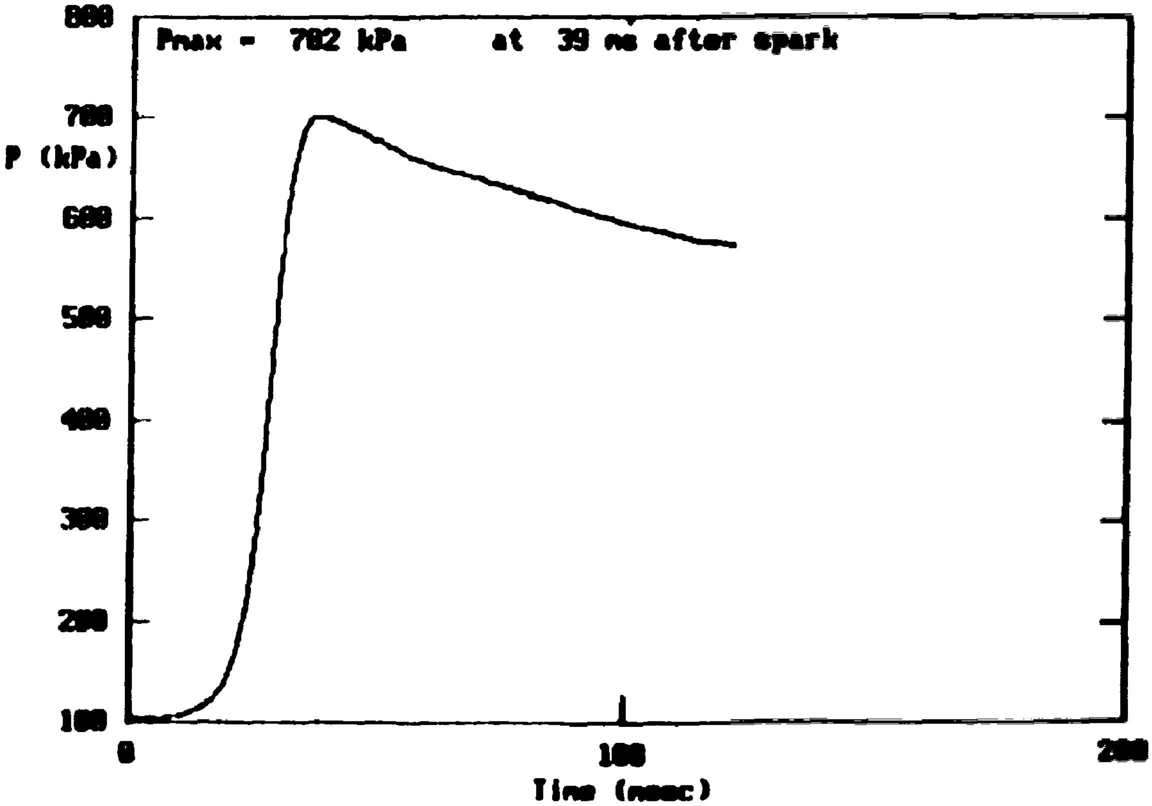

Figure B-18 Pressure variation with time; initial turbulence intensity 1.0 m/s; P_{init} = 1 atm; equivalence ratio 0.85.

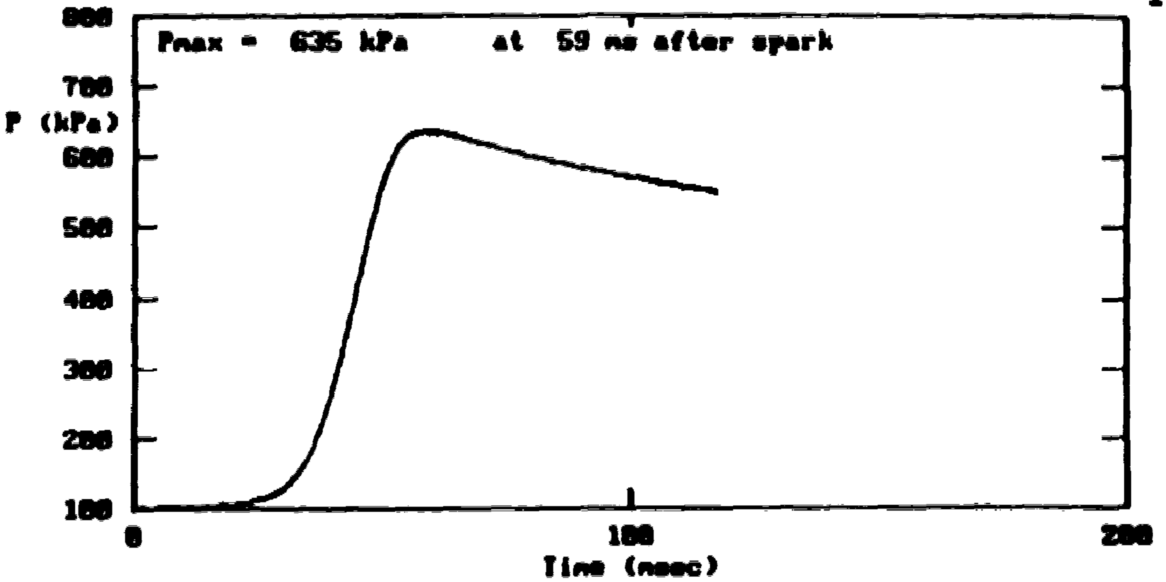

Figure B-19 Pressure variation with time; initial turbulence intensity 1.0 m/s; P_{init} = 1 atm; equivalence ratio 0.75.

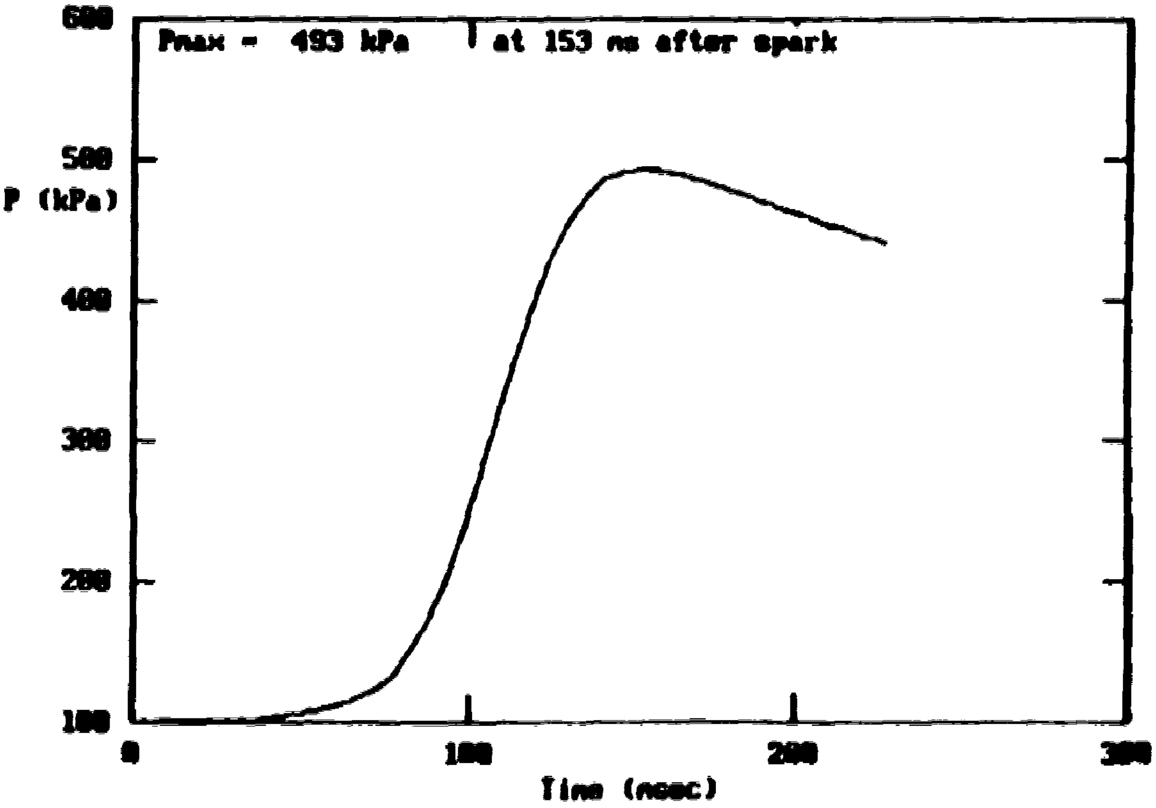

Figure B-20 Pressure variation with time; initial turbulence intensity 1.0 m/s; P_{init} = 1 atm; equivalence ratio 0.6.

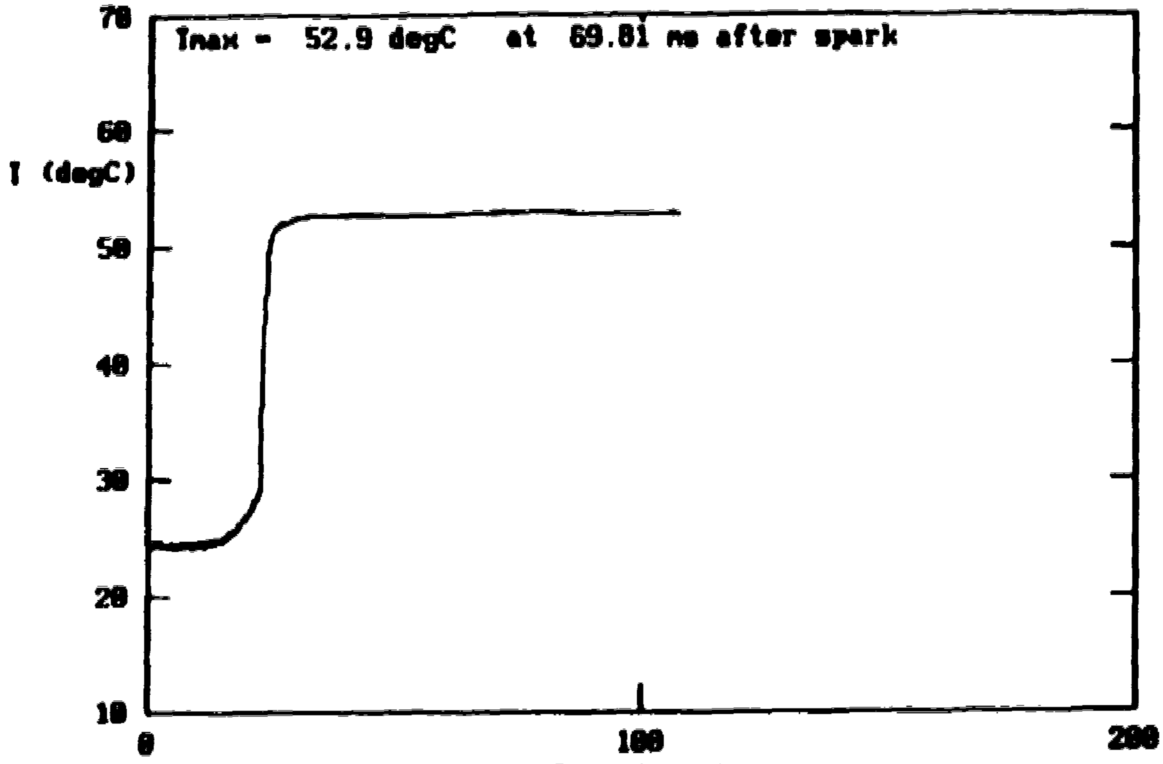

Figure B-21 Wall temperature variation with time; initial turbulence intensity 1.0 m/s; P_{init} = 1 atm; equivalence ratio 1.0.

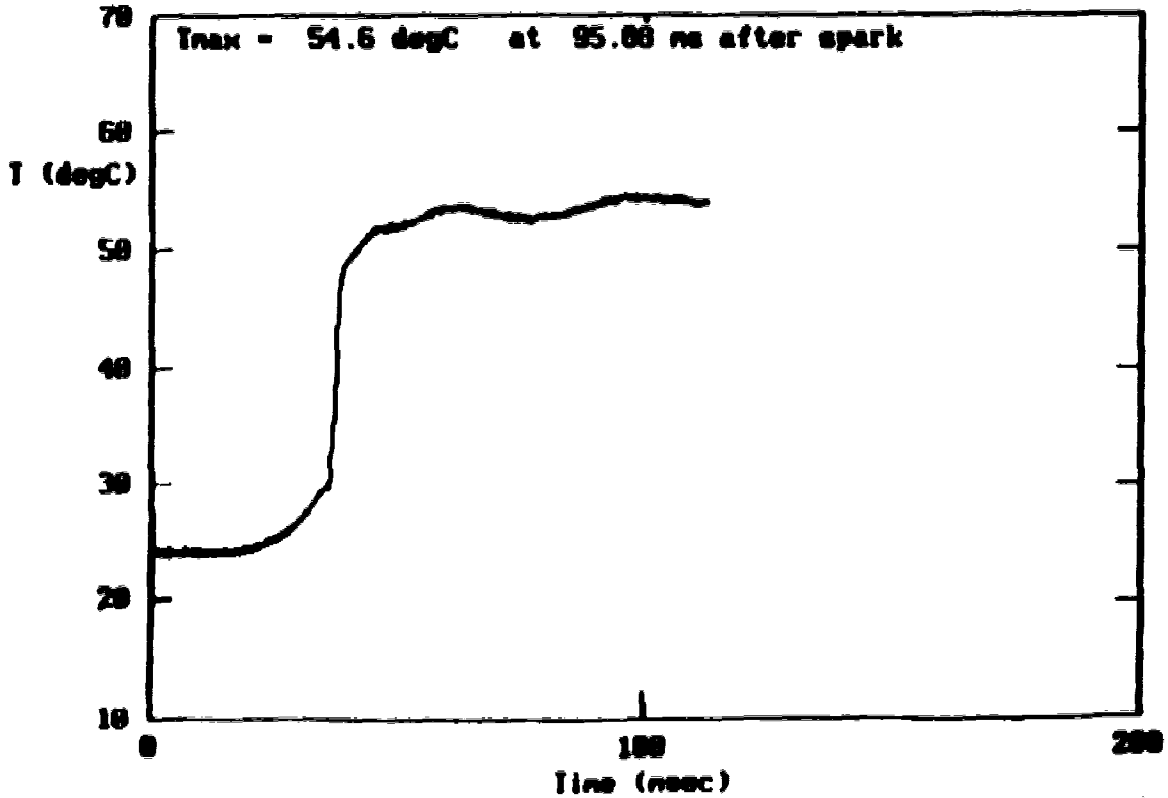

Figure B-22 Wall temperature variation with time; initial turbulence intensity 1.0 m/s; P_{init} = 1 atm; equivalence ratio 0.85.

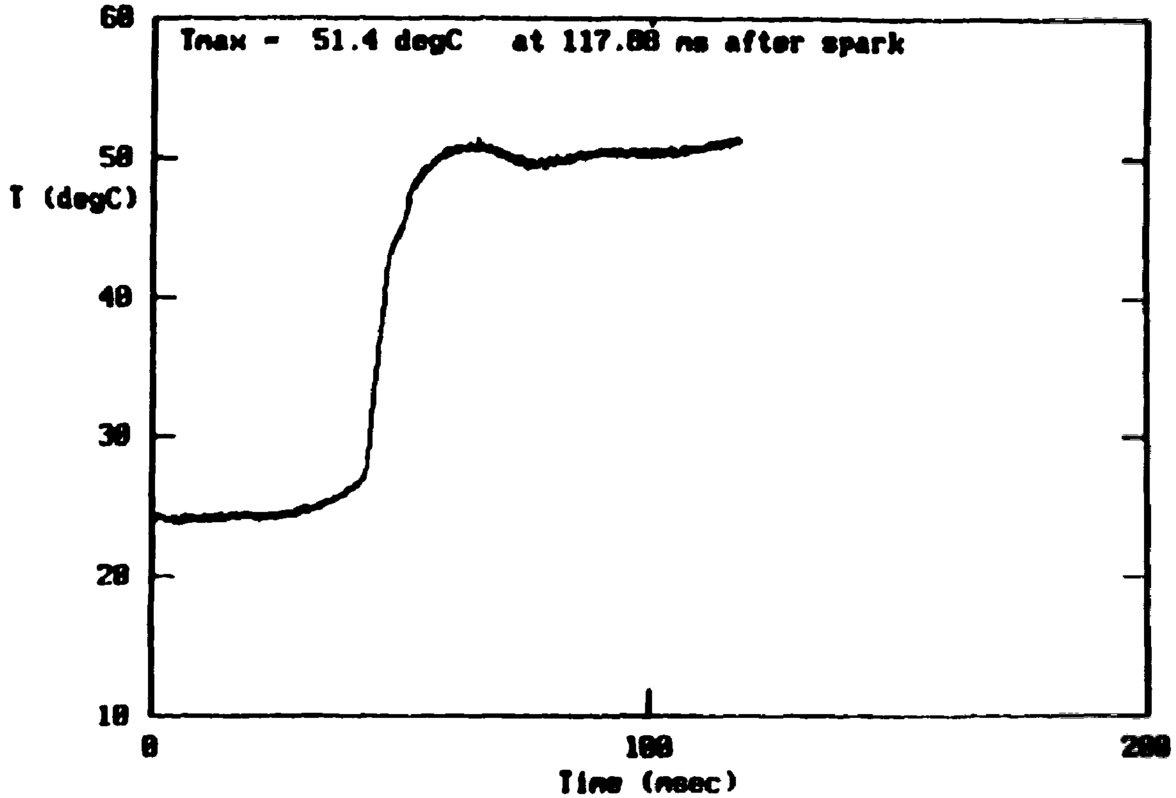

Figure B-23 Wall temperature variation with time; initial turbulence intensity 1.0 m/s; P_{init} = 1 atm; equivalence ratio 0.75.

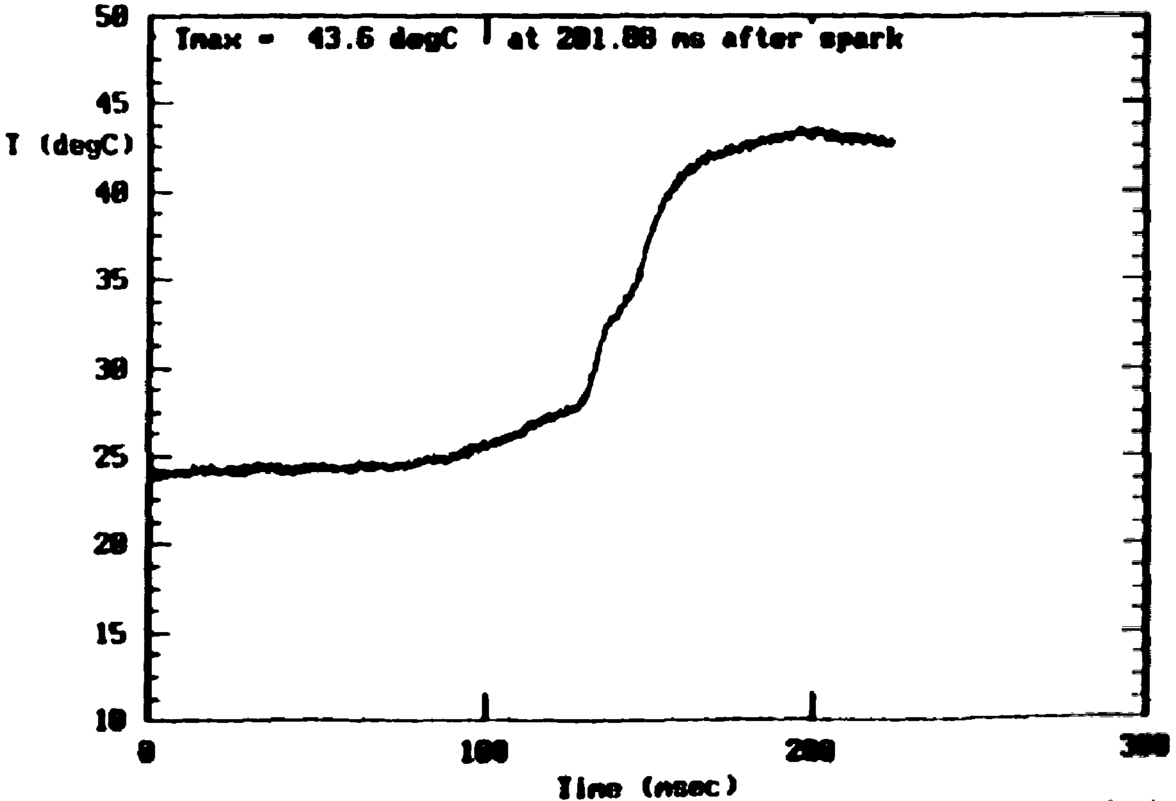

Figure B-24 Wall temperature variation with time; initial turbulence intensity 1.0 m/s; P_{init} = 1 atm; equivalence ratio 0.6.

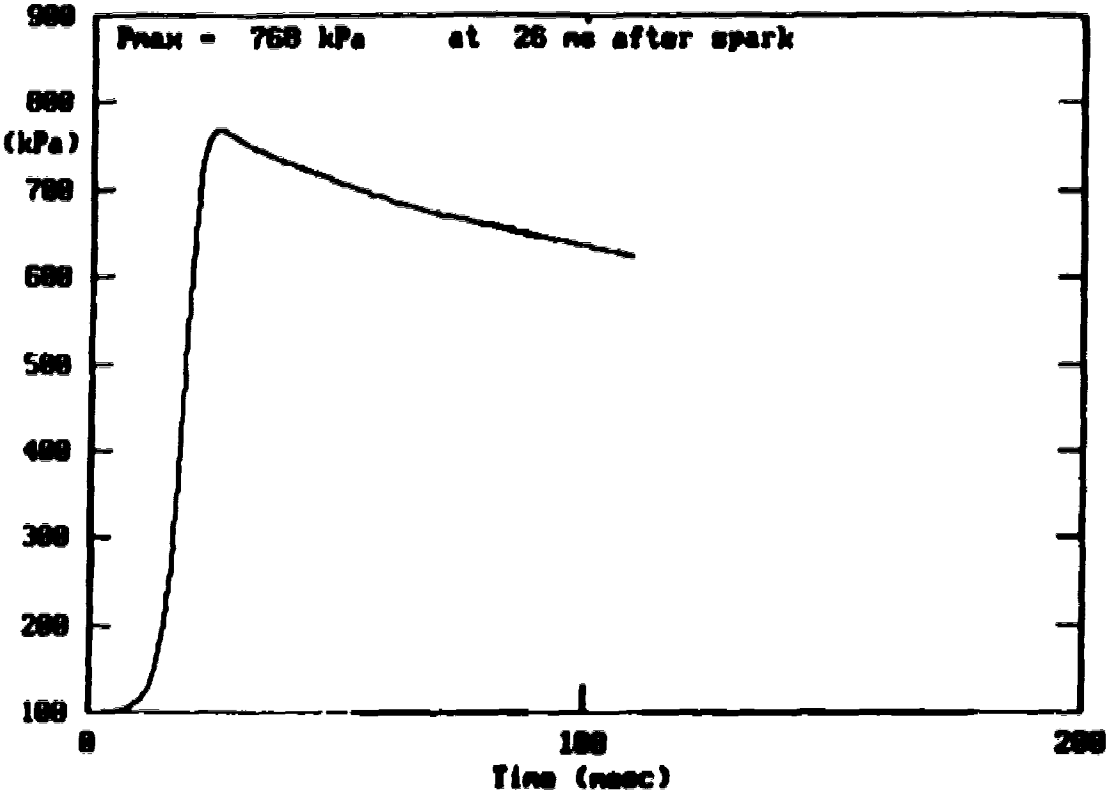

Figure B-25 Pressure variation with time; initial turbulence intensity 1.5 m/s; P_{init} = 1 atm; equivalence ratio 1.0.

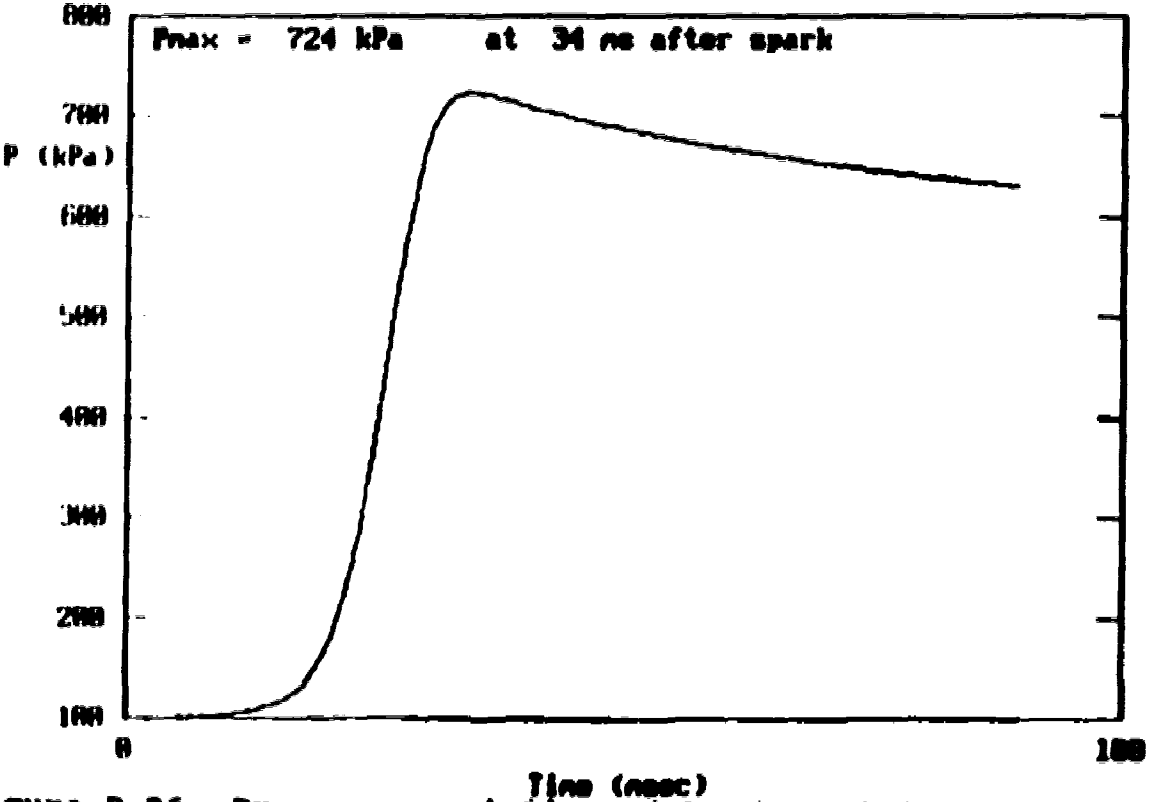

Figure B-26 Pressure variation with time; initial turbulence intensity 1.5 m/s; P_{init} = 1 atm; equivalence ratio 0.85.

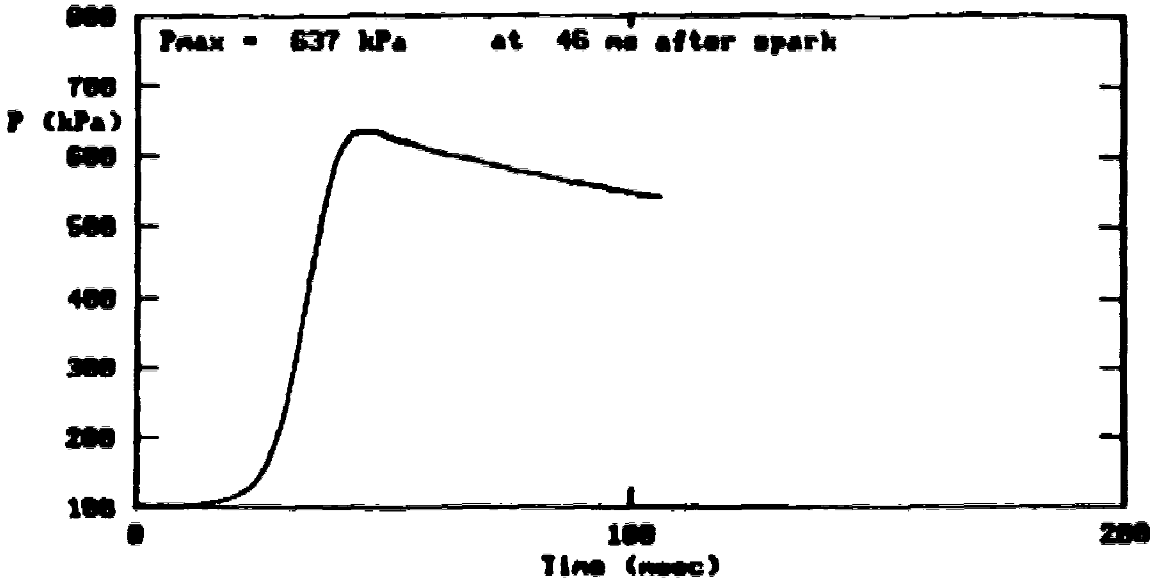

Figure B-27 Pressure variation with time; initial turbulence intensity 1.5 m/s; P_{init} = 1 atm; equivalence ratio 0.75.

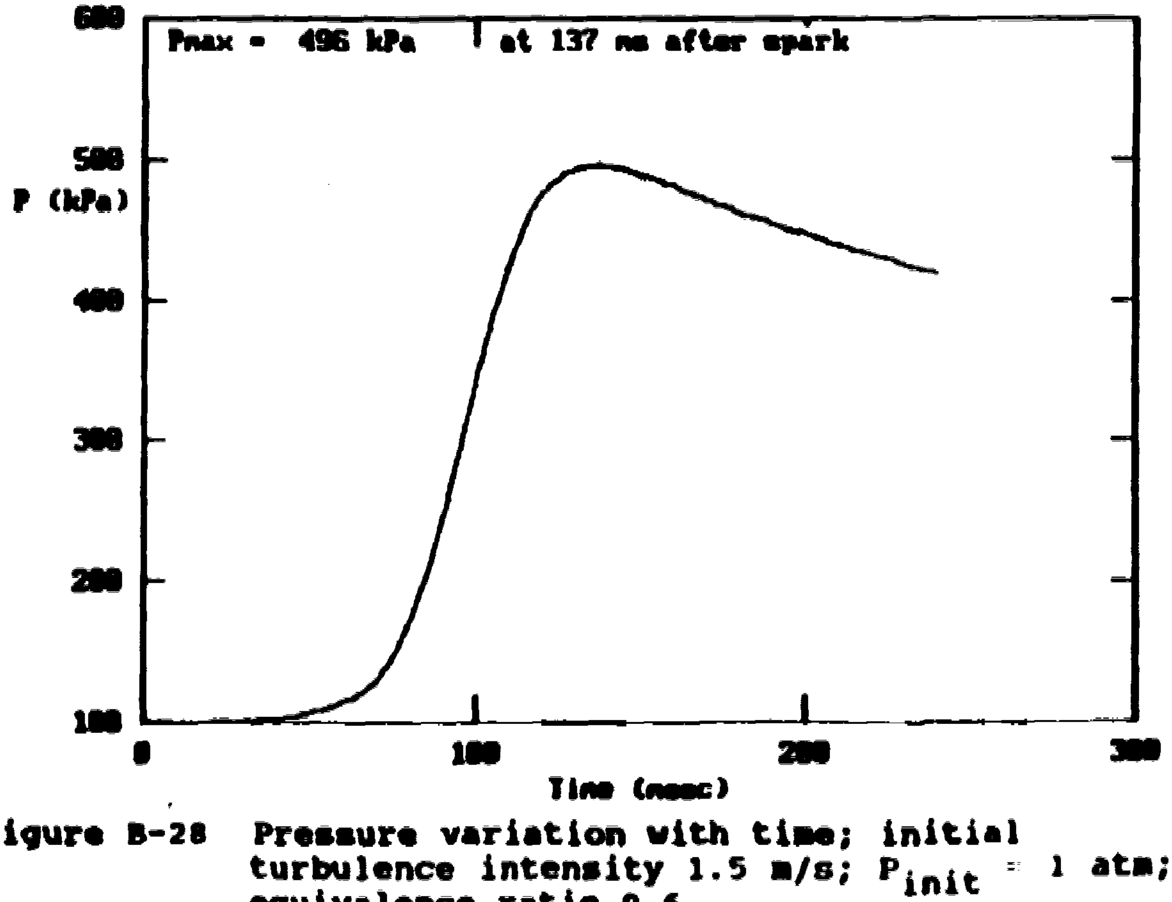

Figure B-28 Pressure variation with time; initial turbulence intensity 1.5 m/s; P_{init} = 1 atm; equivalence ratio 0.6.

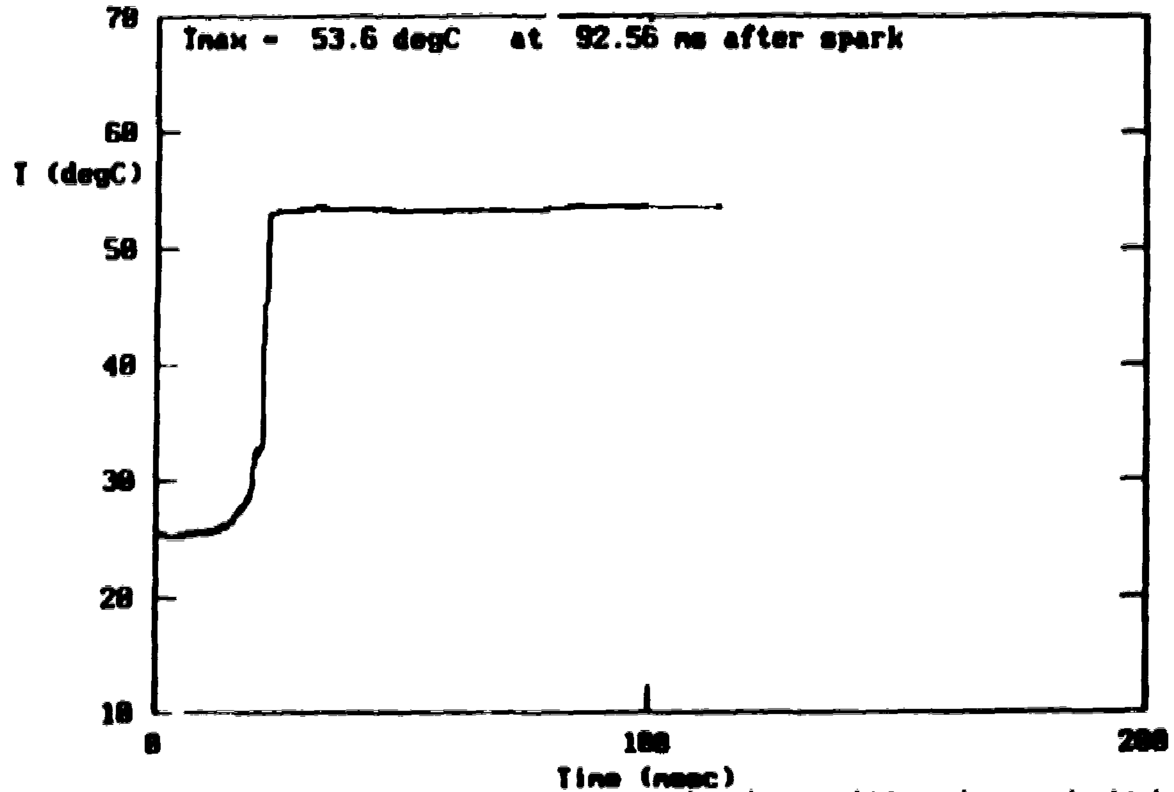

Figure B-29 Wall temperature variation with time; initial turbulence intensity 1.5 m/s; P_{init} = 1 atm; equivalence ratio 1.0.

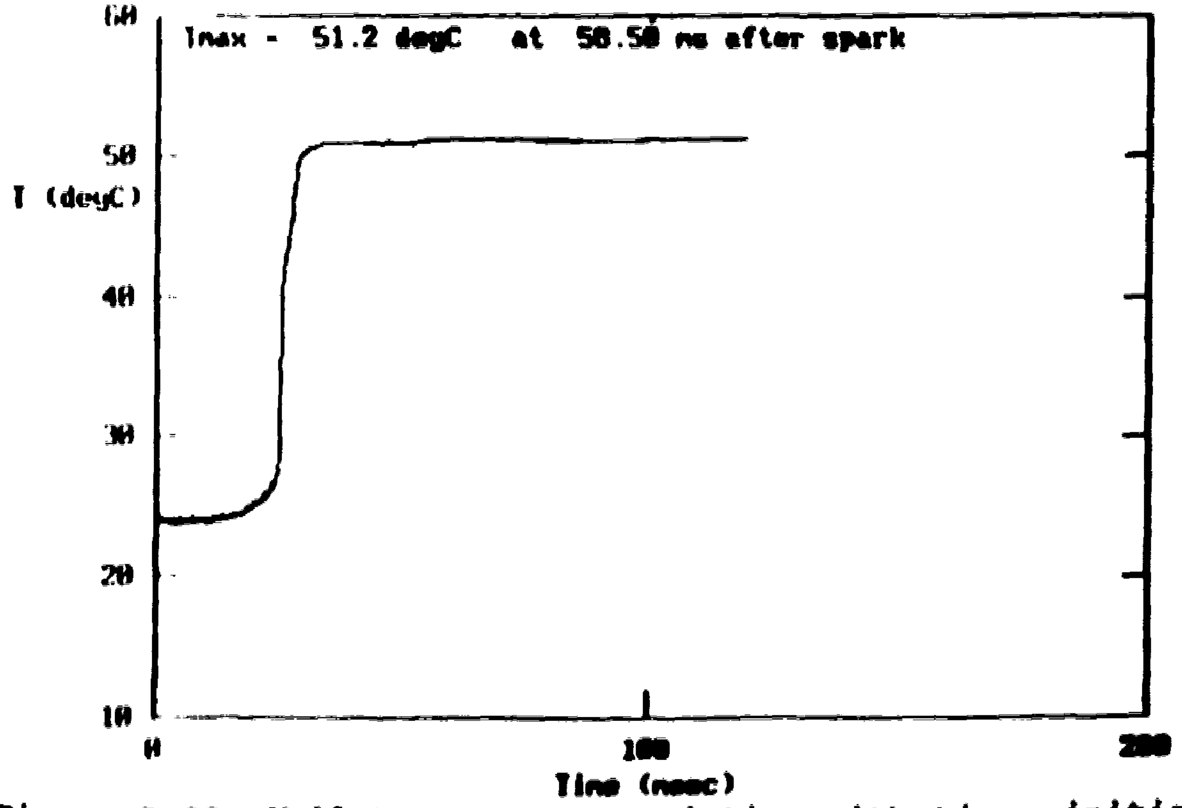

Figure B-30 Wall temperature variation with time; initial turbulence intensity 1.5 m/s; P_{init} = 1 atm; equivalence ratio 0.85.

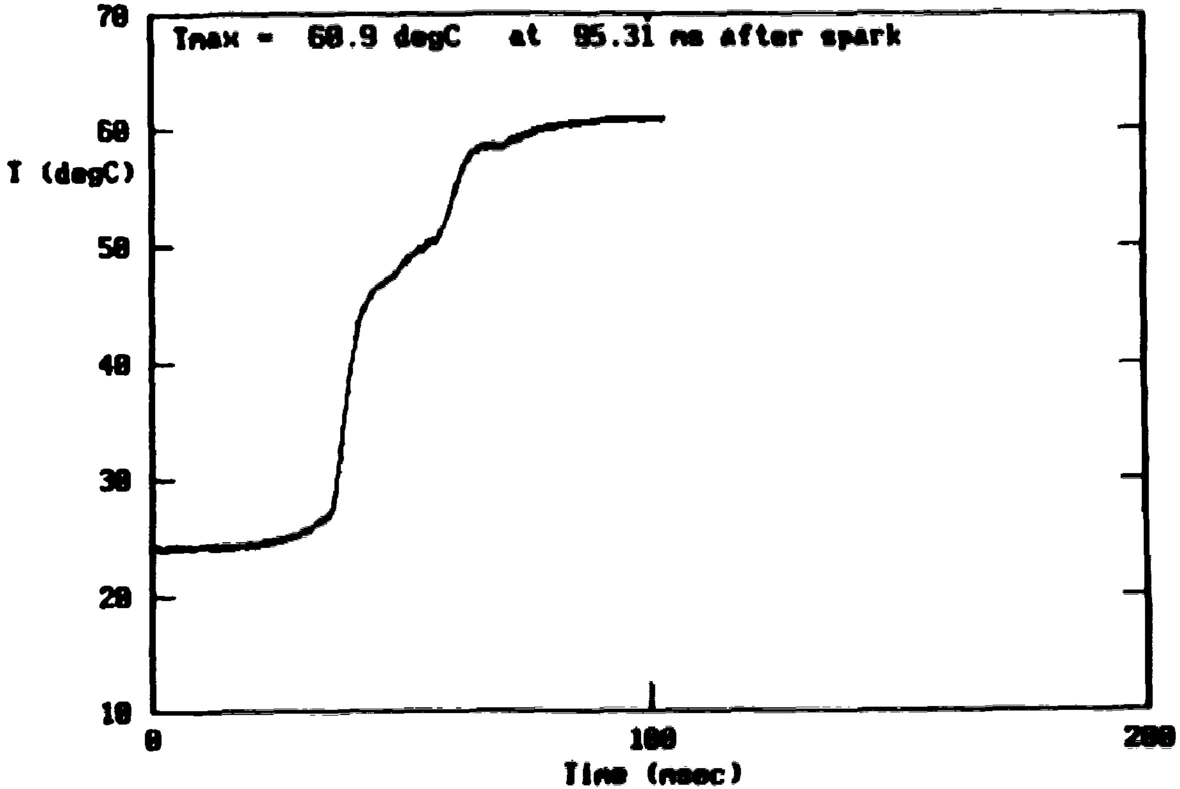

Figure B-31 Wall temperature variation with time; initial turbulence intensity 1.5 m/s; P_{init} = 1 atm; equivalence ratio 0.75.

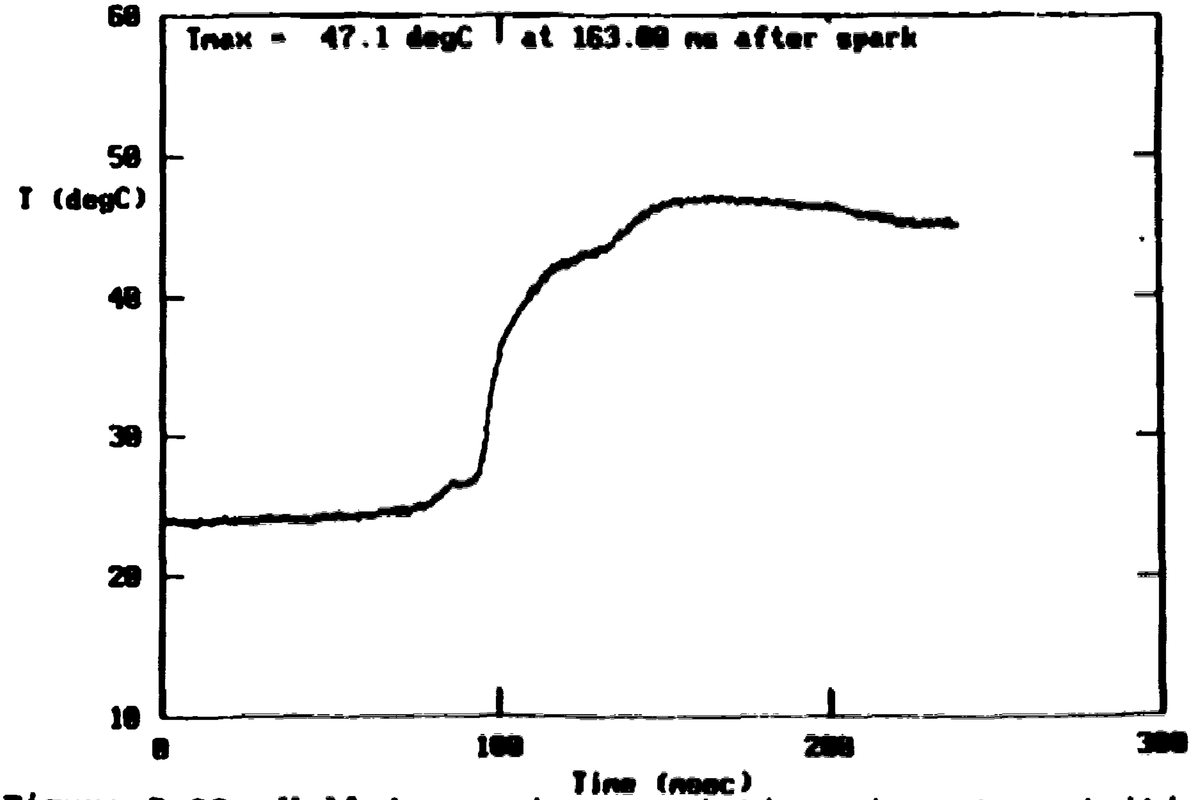

Figure B-32 Wall temperature variation with time; initial turbulence intensity 1.5 m/s; P_{init} = 1 atm; equivalence ratio 0.6.

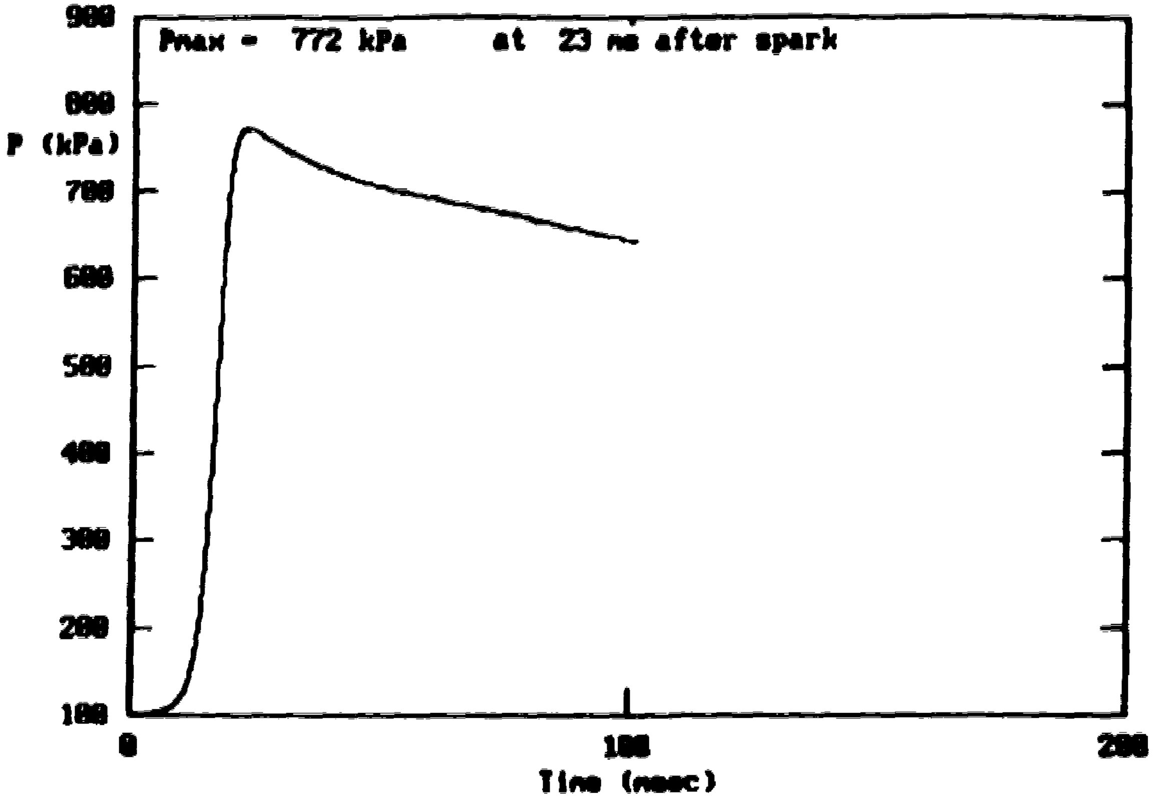

Figure B-33 Pressure variation with time; initial turbulence intensity 2.0 m/s; P_{init} = 1 atm; equivalence ratio 1.0.

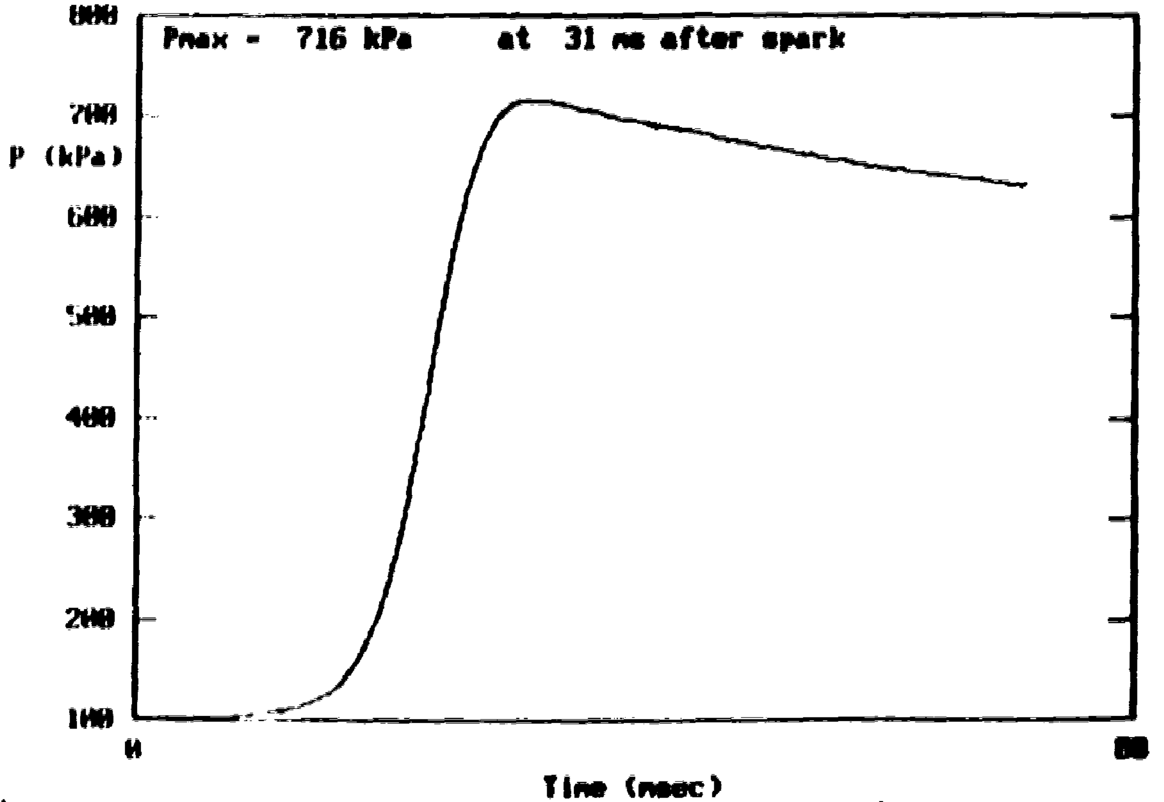

Figure B-34 Pressure variation with time; initial turbulence intensity 2.0 m/s; P_{init} = 1 atm; equivalence ratio 0.85.

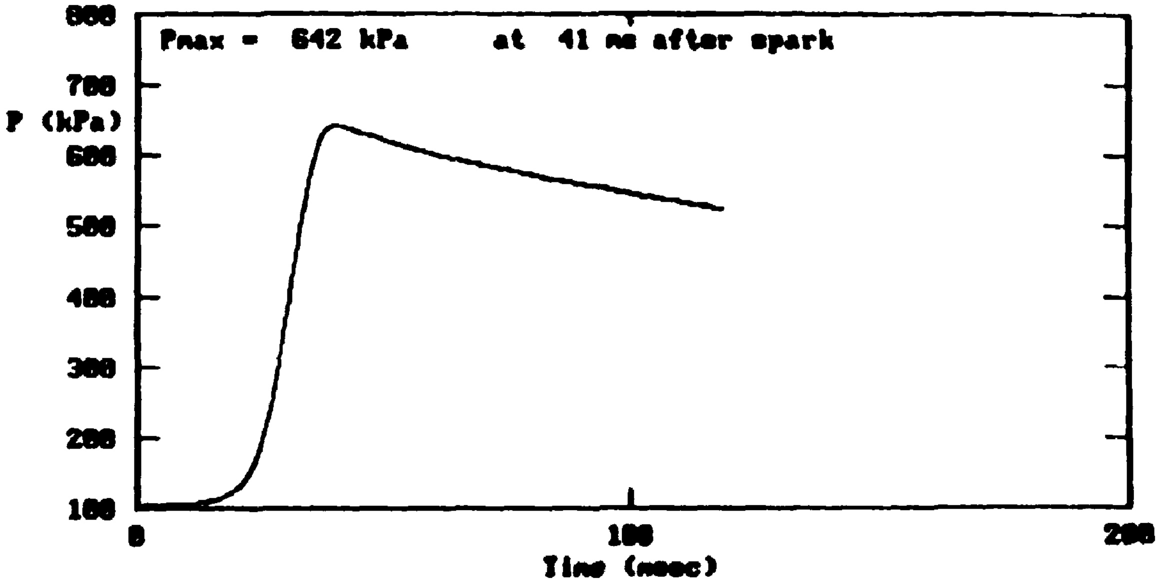

Figure B-35 Pressure variation with time; initial turbulence intensity 2.0 m/s; P_{init} = 1 atm; equivalence ratio 0.75.

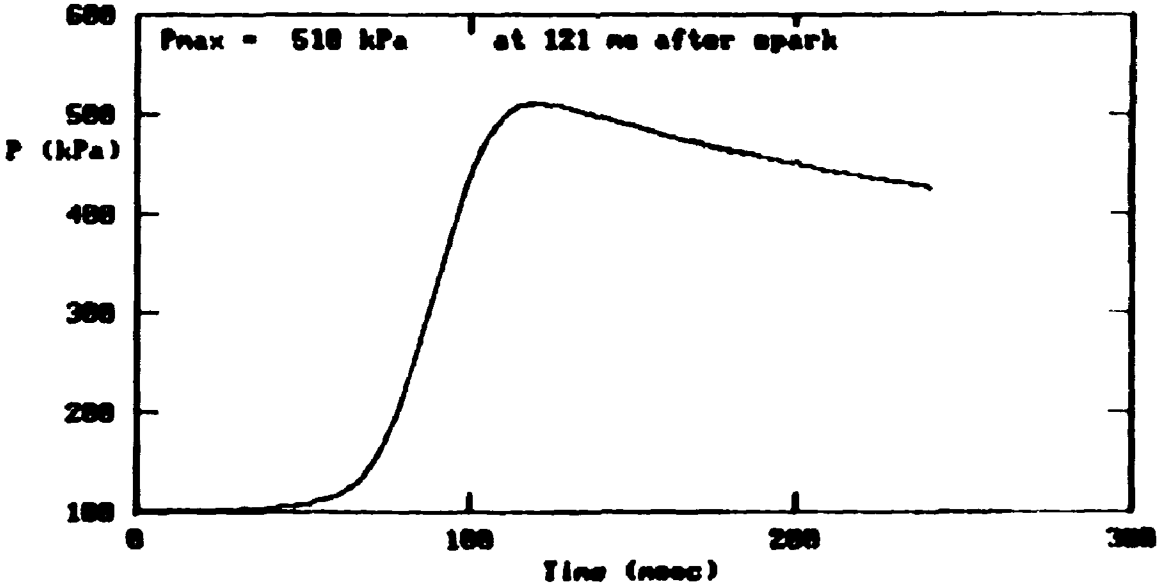

Figure B-36 Pressure variation with time; initial turbulence intensity 2.0 m/s; P_{init} = 1 atm; equivalence ratio 0.6.

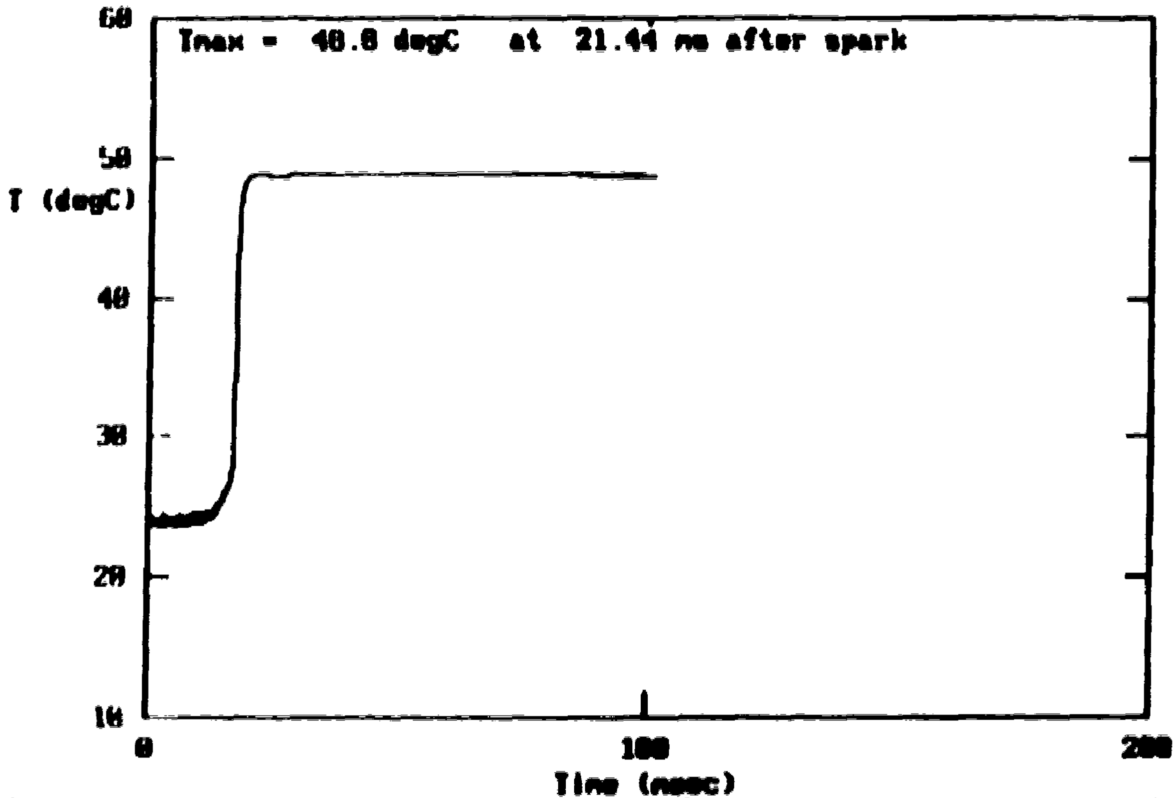

Figure B-37 Wall temperature variation with time; initial turbulence intensity 2.0 m/s; P_{init} = 1 atm; equivalence ratio 1.0.

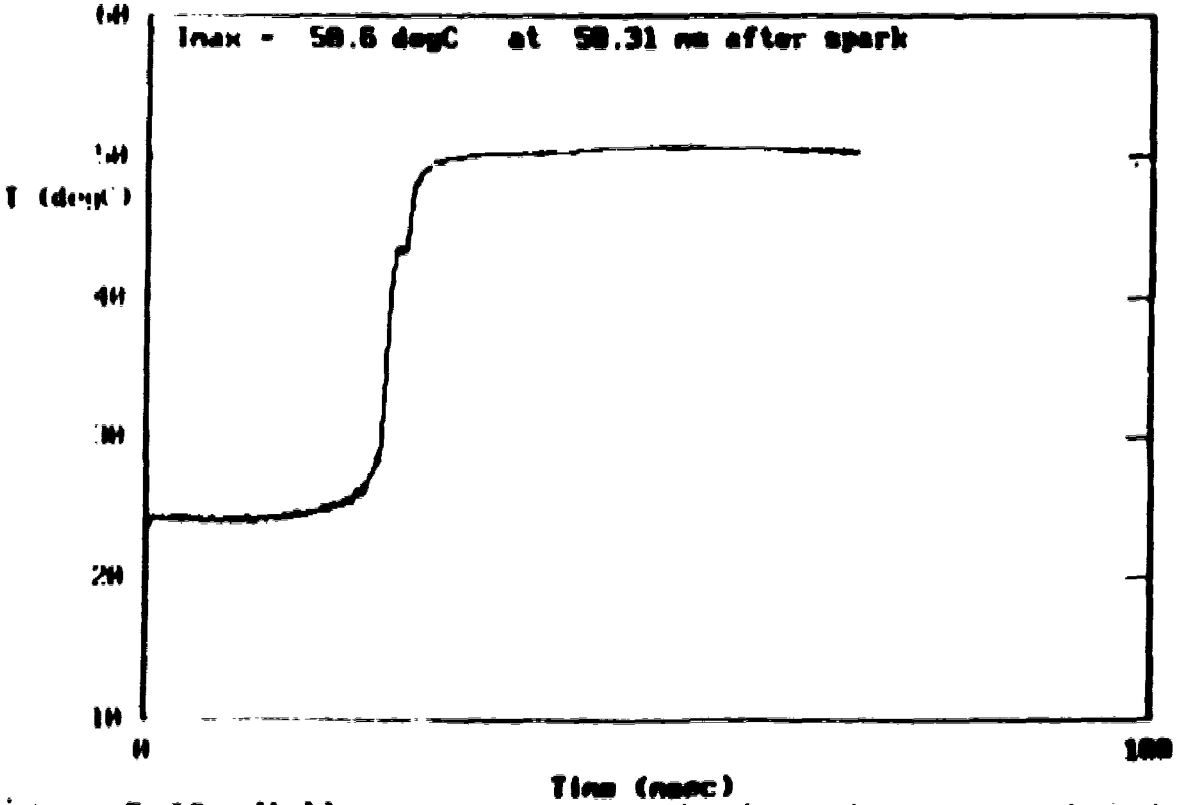

Figure B-38 Wall temperature variation with time; initial turbulence intensity 2.0 m/s; P_{init} = 1 atm; equivalence ratio 0.85.

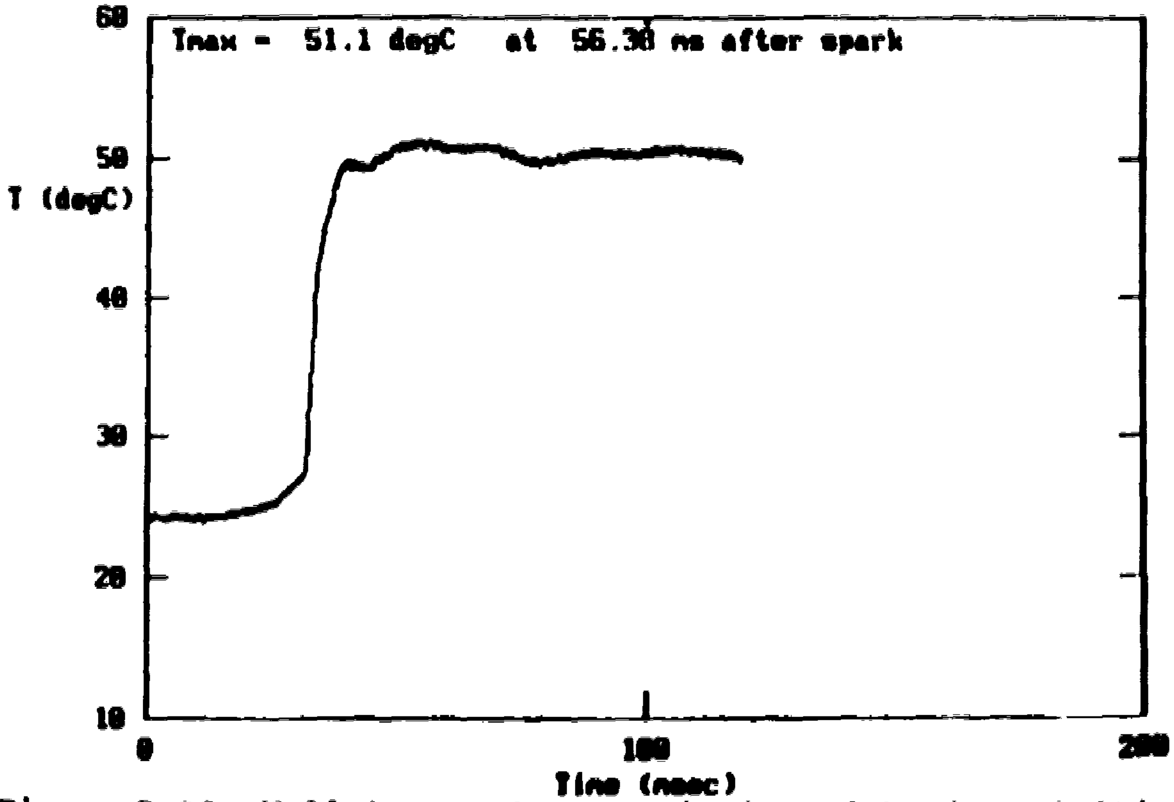

Figure B-39 Wall temperature variation with time; initial turbulence intensity 2.0 m/s; P_{init} = 1 atm; equivalence ratio 0.75.

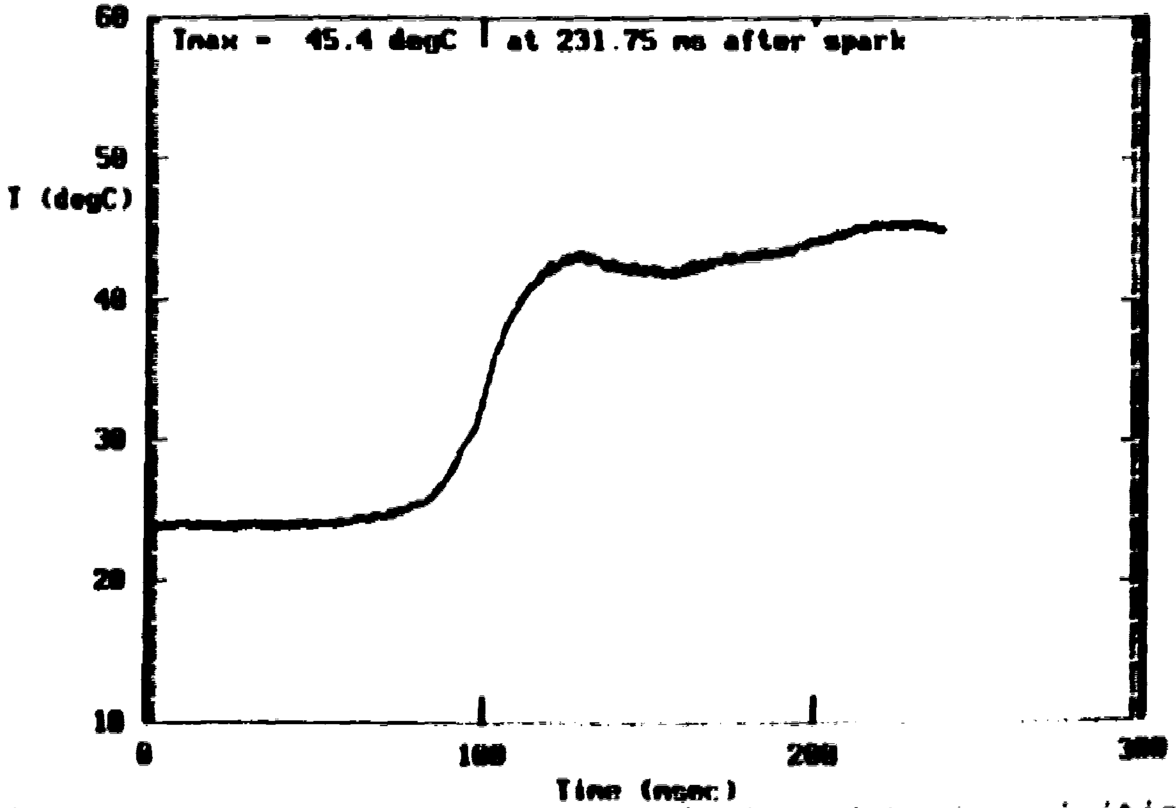

Figure B-40 Wall temperature variation with time; initial turbulence intensity 2.0 m/s; P_{init} 1 atm; equivalence ratio 0.6.

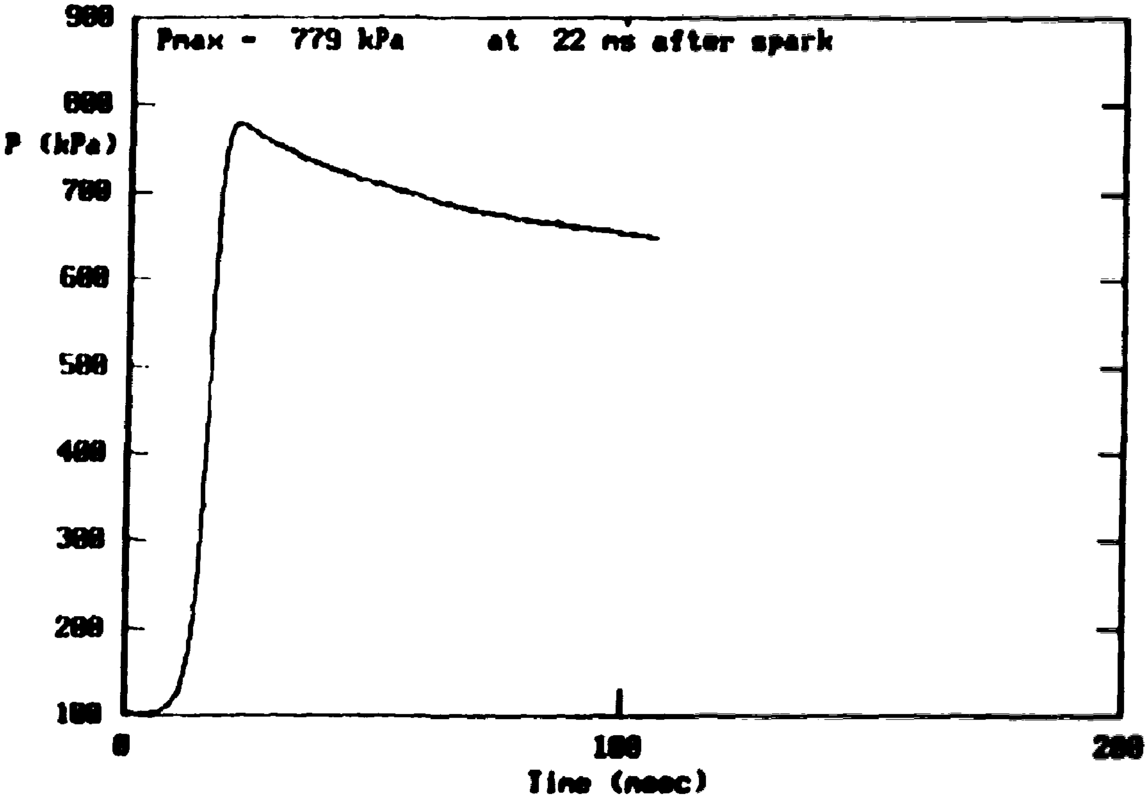

Figure B-41 Pressure variation with time; initial turbulence intensity 2.5 m/s; P_{init} = 1 atm; equivalence ratio 1.0.

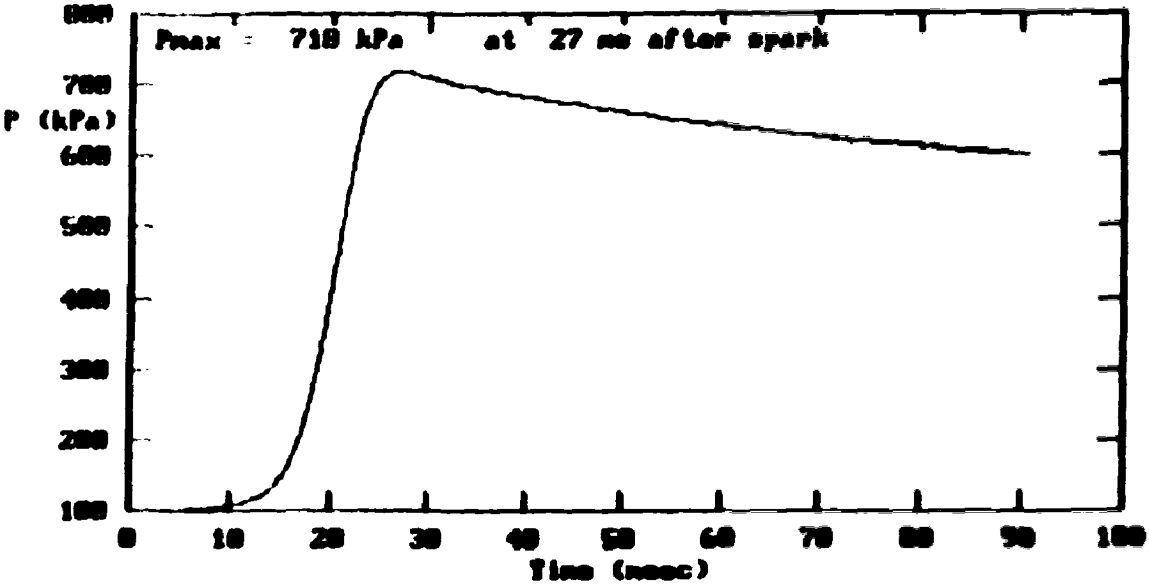

Figure B-42 Pressure variation with time; initial turbulence intensity 2.5 m/s; P_{init} = 1 atm; equivalence ratio 0.85.

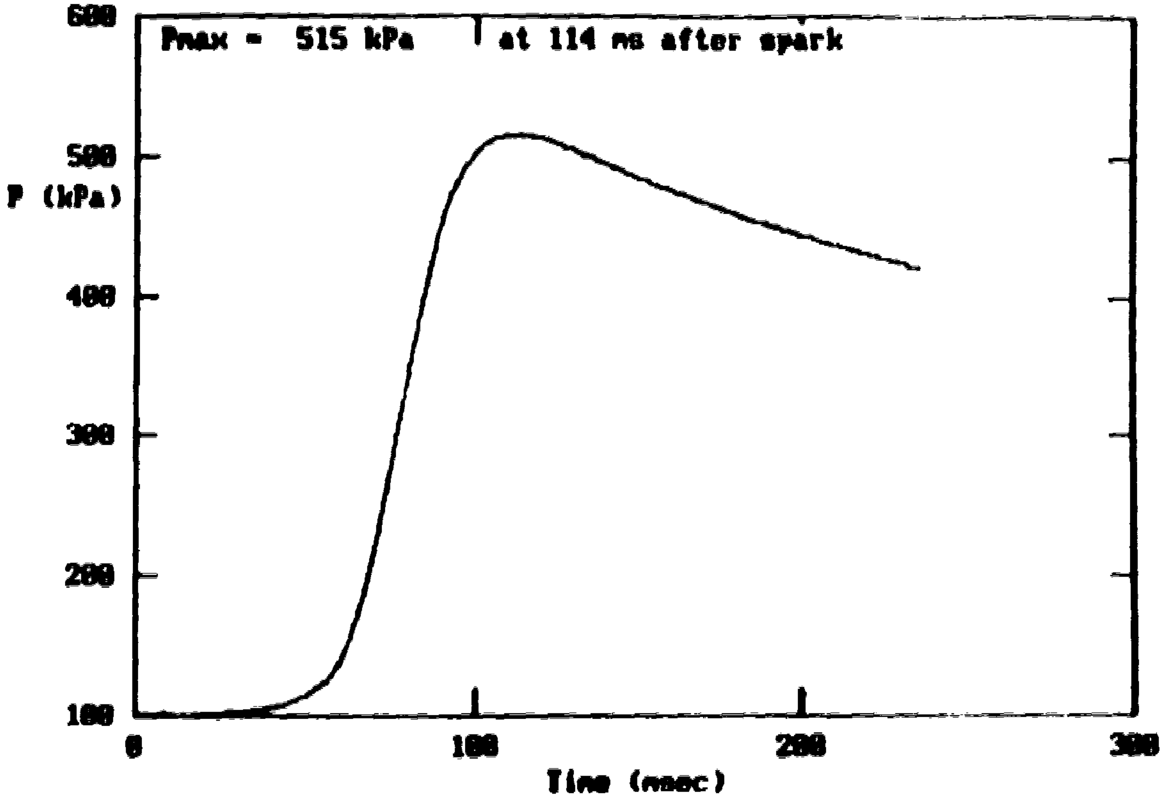

Figure B-43 Pressure variation with time; initial turbulence intensity 2.5 m/s; P_{init} = 1 atm; equivalence ratio 0.6.

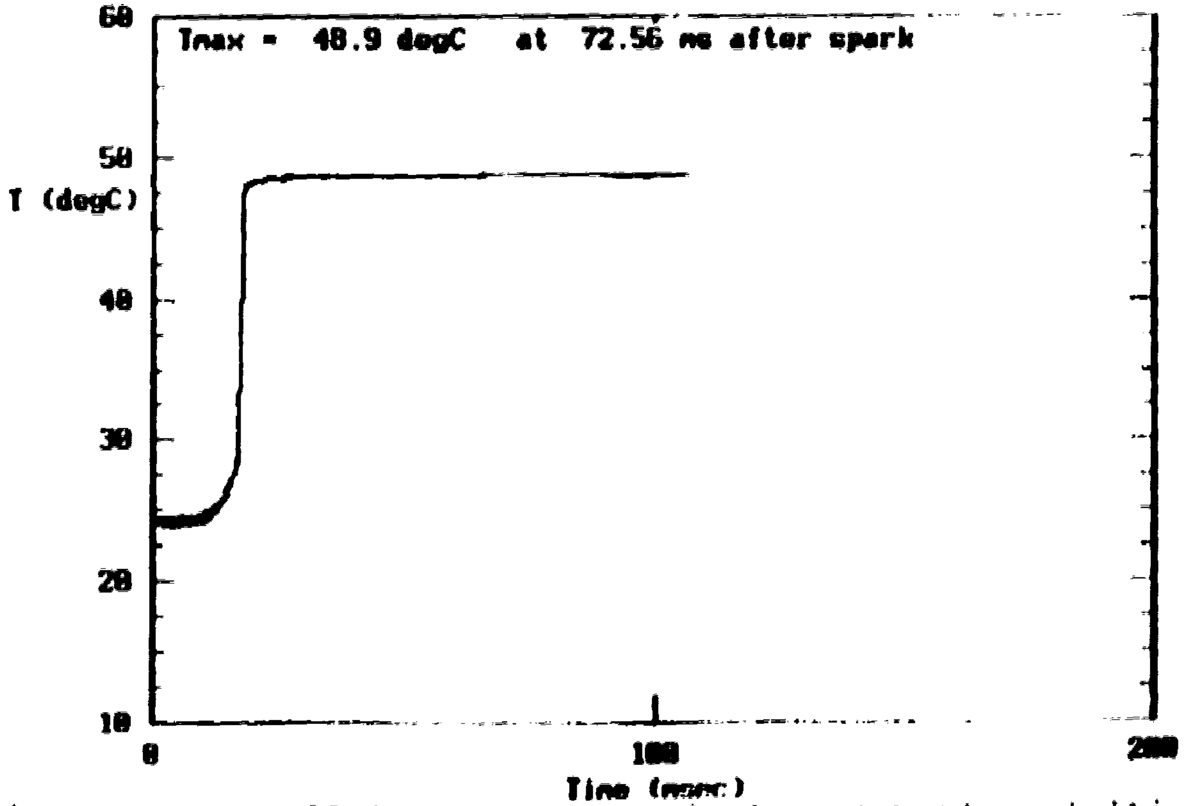

Figure B-44 Wall temperature variation with time; initial turbulence intensity 2.5 m/s; P_{init} = 1 atm; equivalence ratio 1.0.

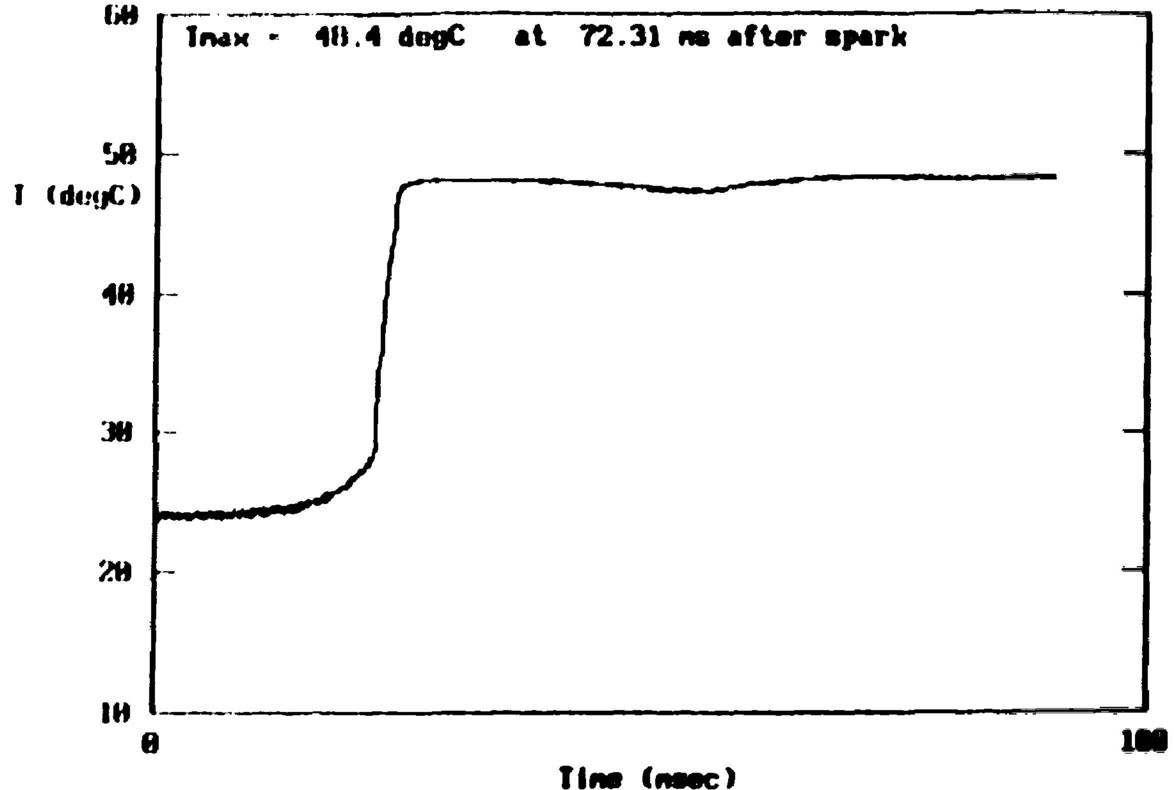

Figure B-45 Wall temperature variation with time; initial turbulence intensity 2.5 m/s; P_{init} = 1 atm; equivalence ratio 0.85.

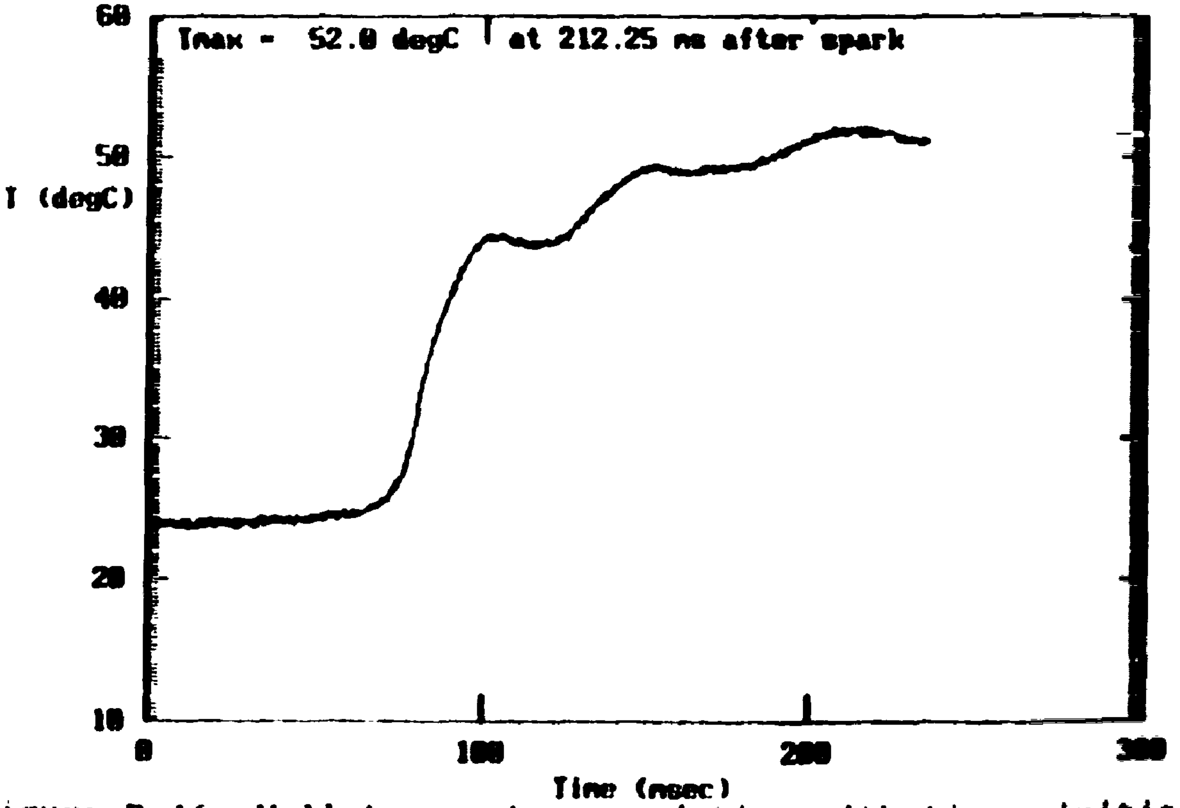

Figure B-46 Wall temperature variation with time; initial turbulence intensity 2.5 m/s; P_{init} = 1 atm; equivalence ratio 0.6.

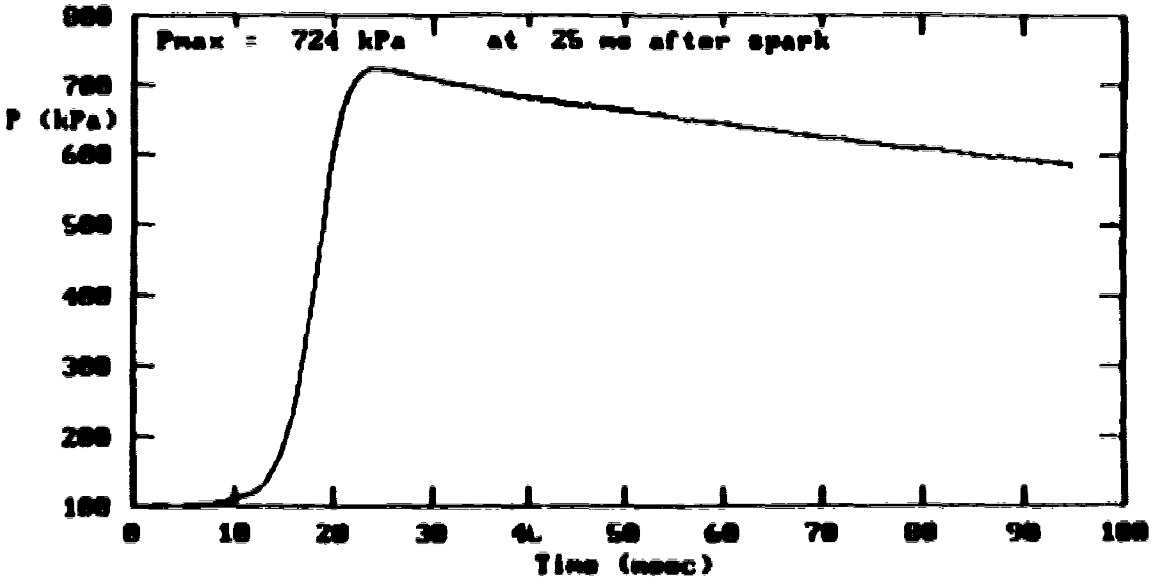

Figure B-47 Pressure variation with time; initial turbulence intensity 3.0 m/s; P_{init} = 1 atm; equivalence ratio 0.85.

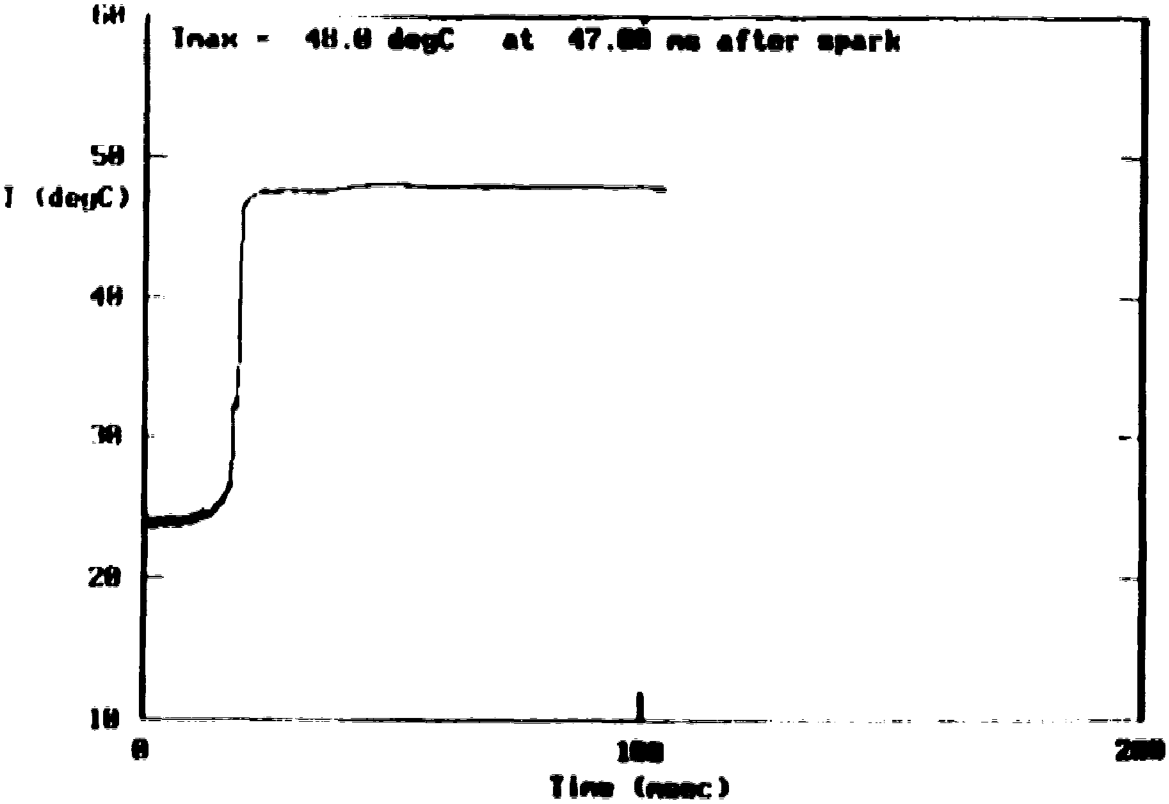

Figure B-48 Wall temperature variation with time; initial turbulence intensity 3.0 m/s; P_{init} = 1 atm; equivalence ratio 0.85

APPENDIX C

Representative experimental heat flux results were presented in Chapter 4. The remaining results are presented in this appendix.

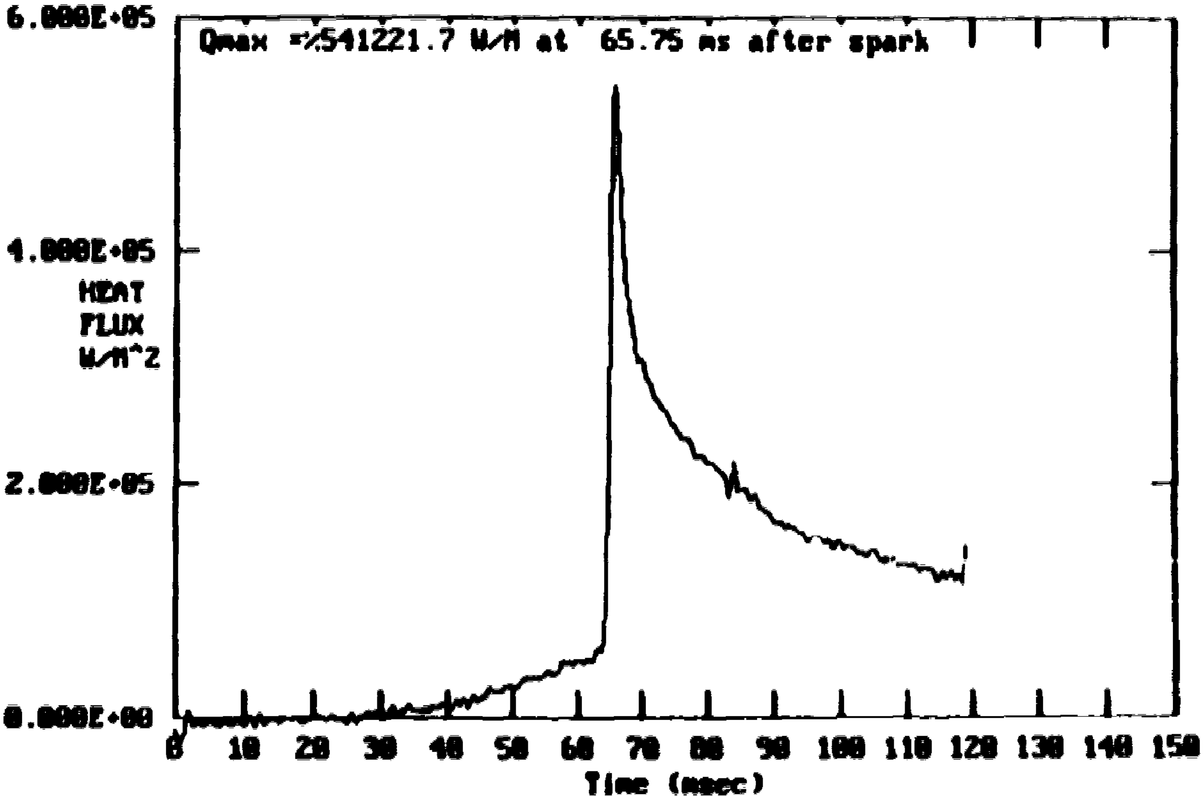

Figure C-1 Wall heat flux variation with time; laminar combustion; P_{init} = 1 atm; equivalence ratio 0.85.

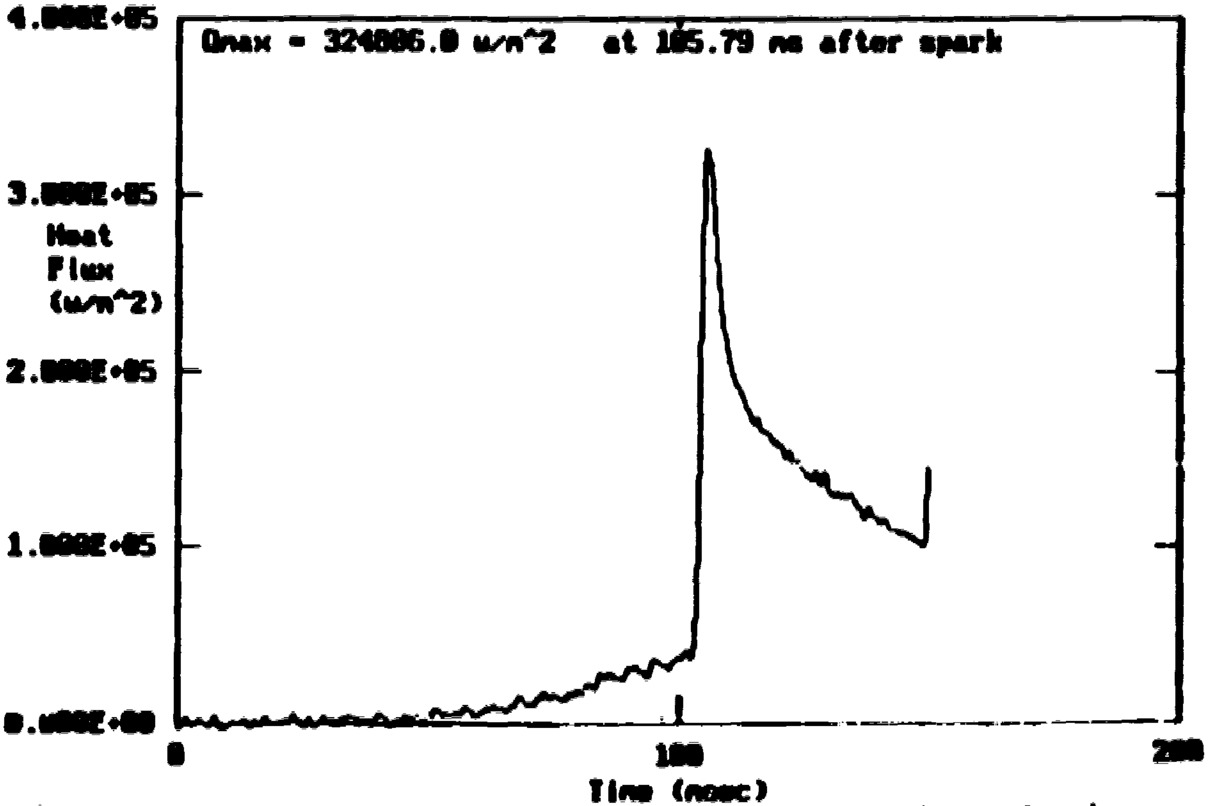

Figure C-2 Wall heat flux variation with time; laminar combustion; P_{init} = 1 atm; equivalence ratio 0.75.

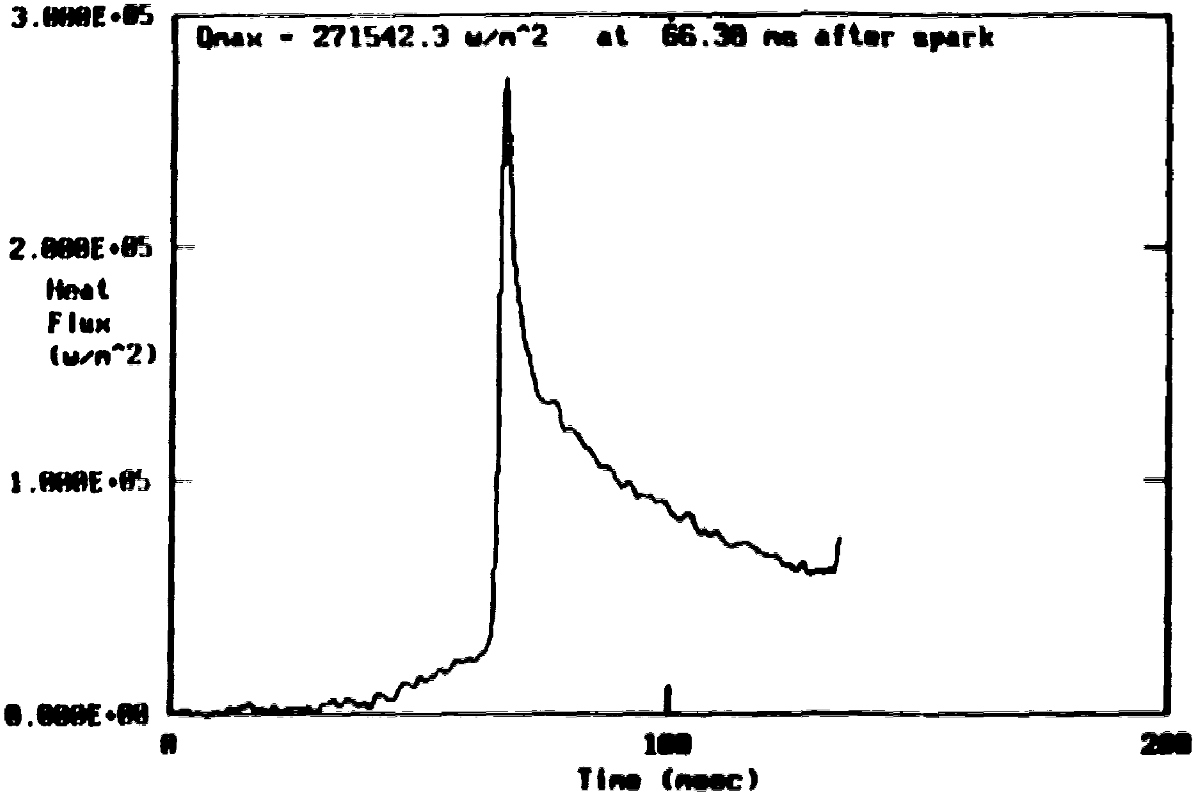

Figure C-3 Wall heat flux variation with time; laminar combustion; P_{init} = 0.5 atm; equivalence ratio 0.75.

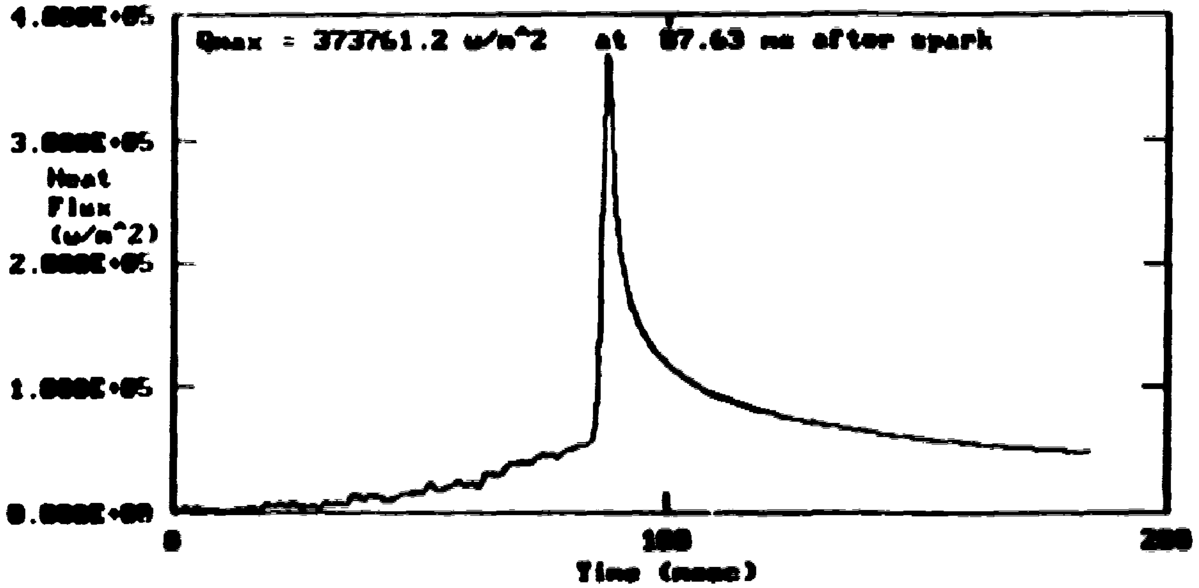

Figure C-4 Wall heat flux variation with time; laminar combustion; P_{init} = 1.5 atm; equivalence ratio 0.75.

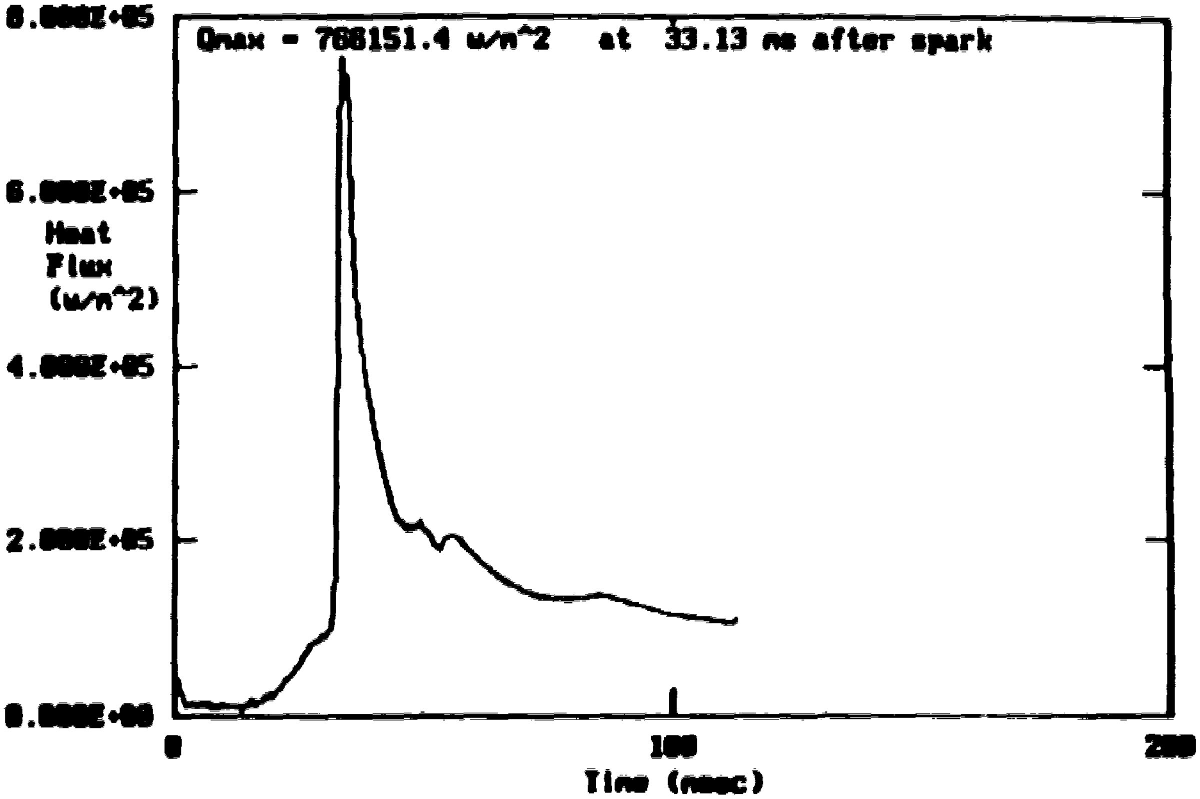

Figure C-5 Wall heat flux variation with time; initial turbulence intensity 0.5 m/s; P_{init} = 1 atm; equivalence ratio 1.0.

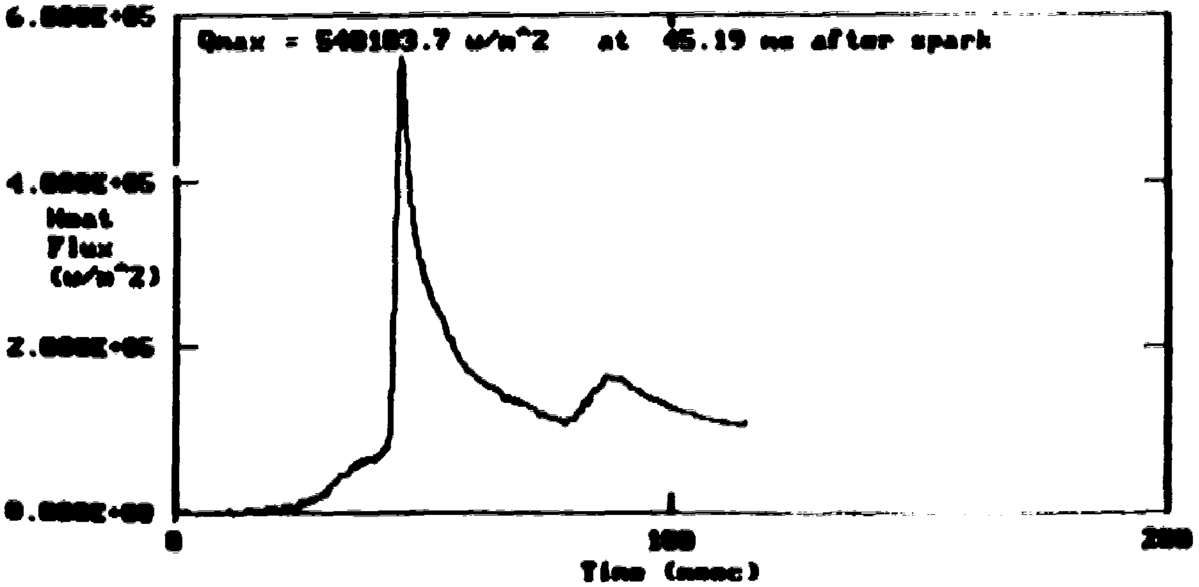

Figure C-6 Wall heat flux variation with time; initial turbulence intensity 0.5 m/s; P_{init} = 1 atm; equivalence ratio 0.85.

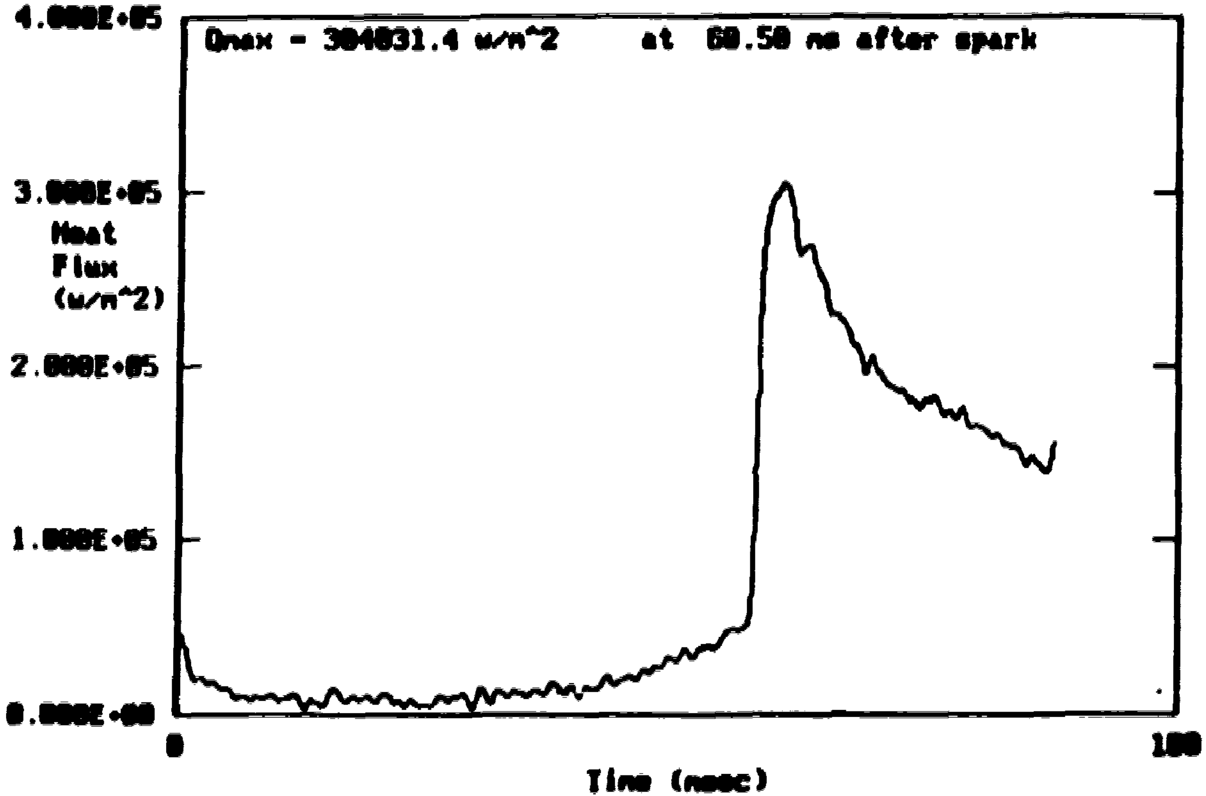

Figure C-7 Wall heat flux variation with time; initial turbulence intensity 0.5 m/s; P_{init} = 1 atm; equivalence ratio 0.75.

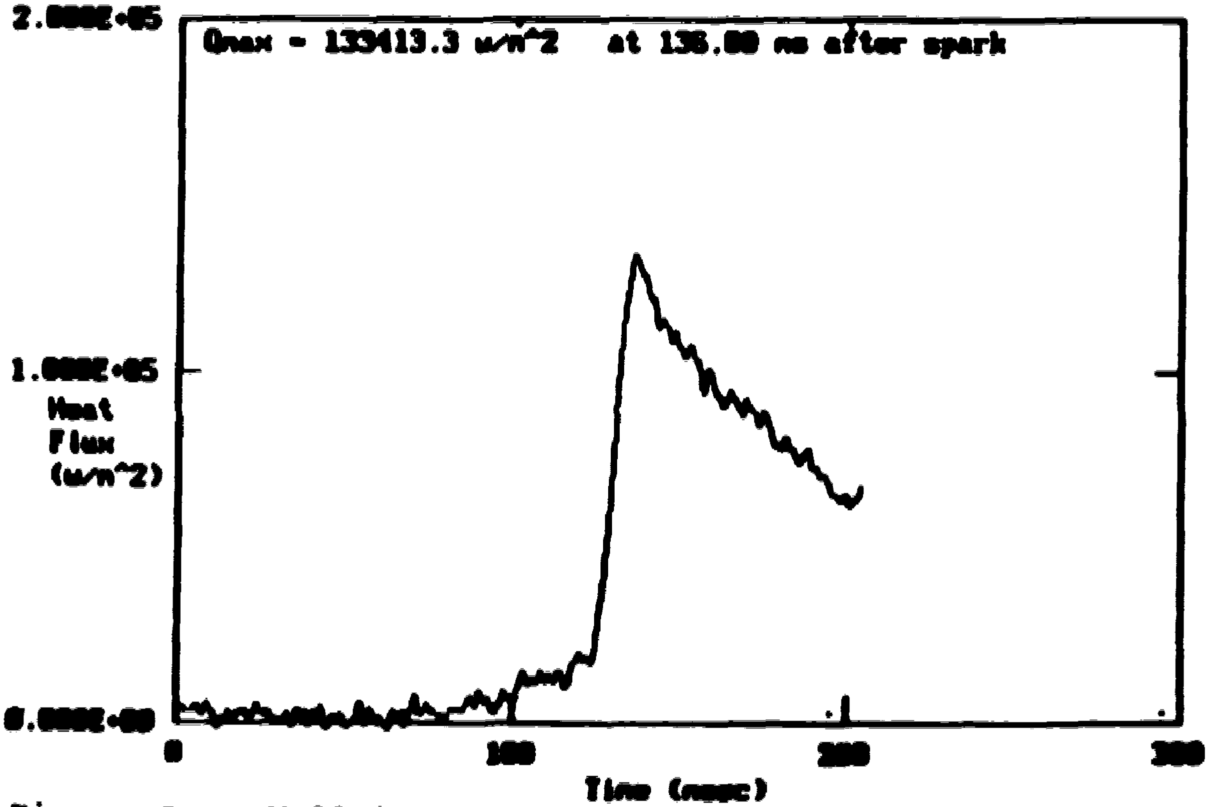

Figure C-8 Wall heat flux variation with time; initial turbulence intensity 0.5 m/s; P_{init} = 1 atm; equivalence ratio 0.6.

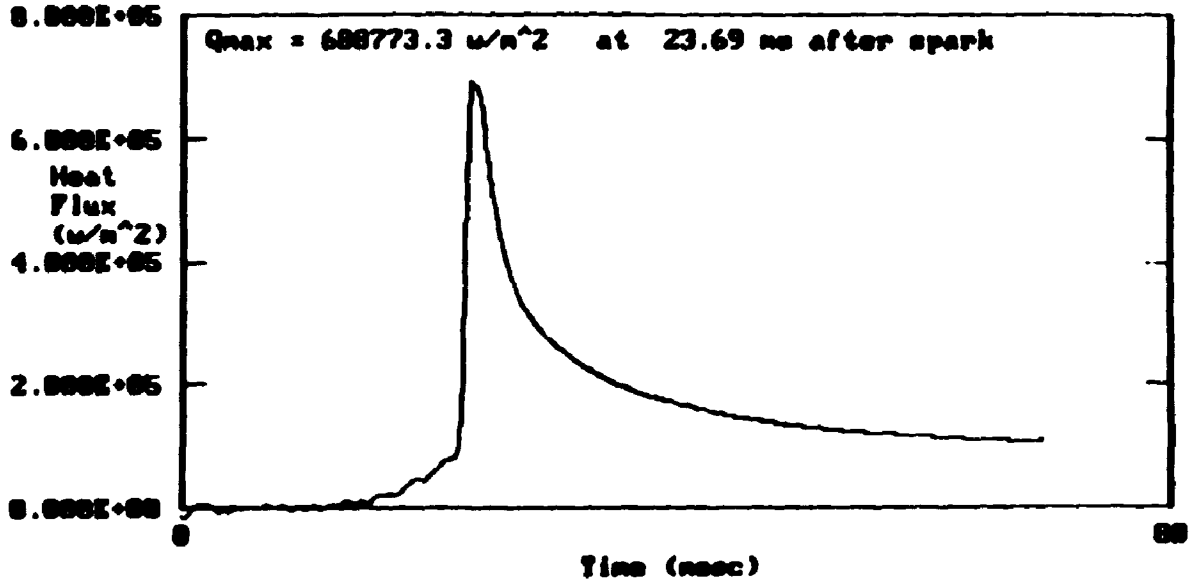

Figure C-9 Wall heat flux variation with time; initial turbulence intensity 1.0 m/s; P_{init} = 1 atm; equivalence ratio 1.0.

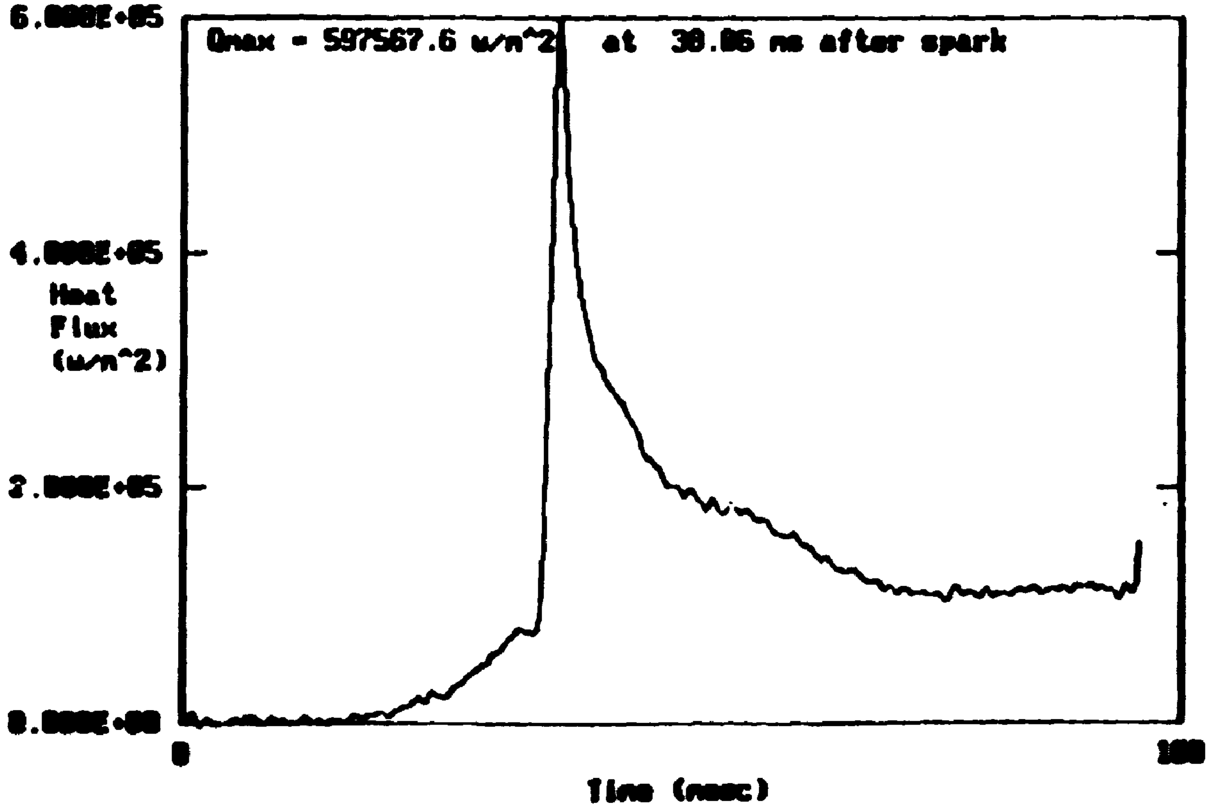

Figure C-10 Wall heat flux variation with time; initial turbulence intensity 1.0 m/s; P_{init} = 1 atm; equivalence ratio 0.85.

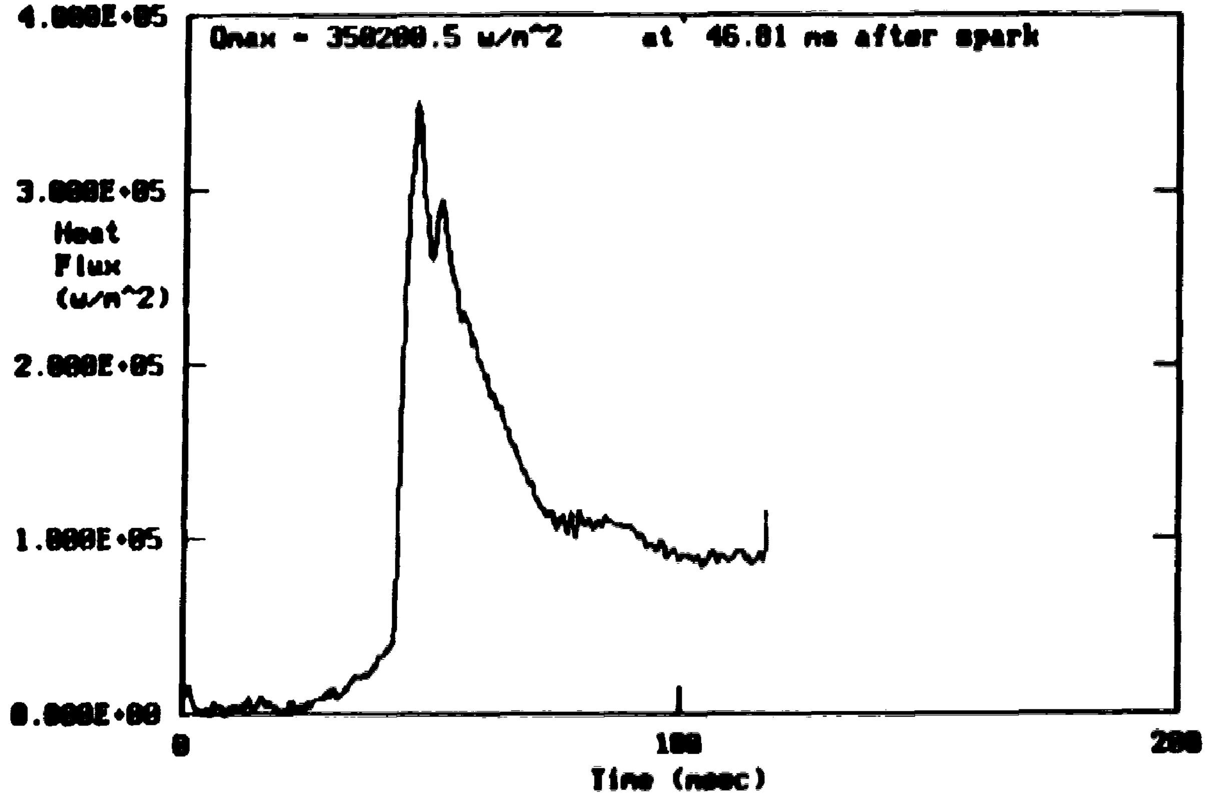

Figure C-11 Wall heat flux variation with time; initial turbulence intensity 1.0 m/s; P_{init} = 1 atm; equivalence ratio 0.75.

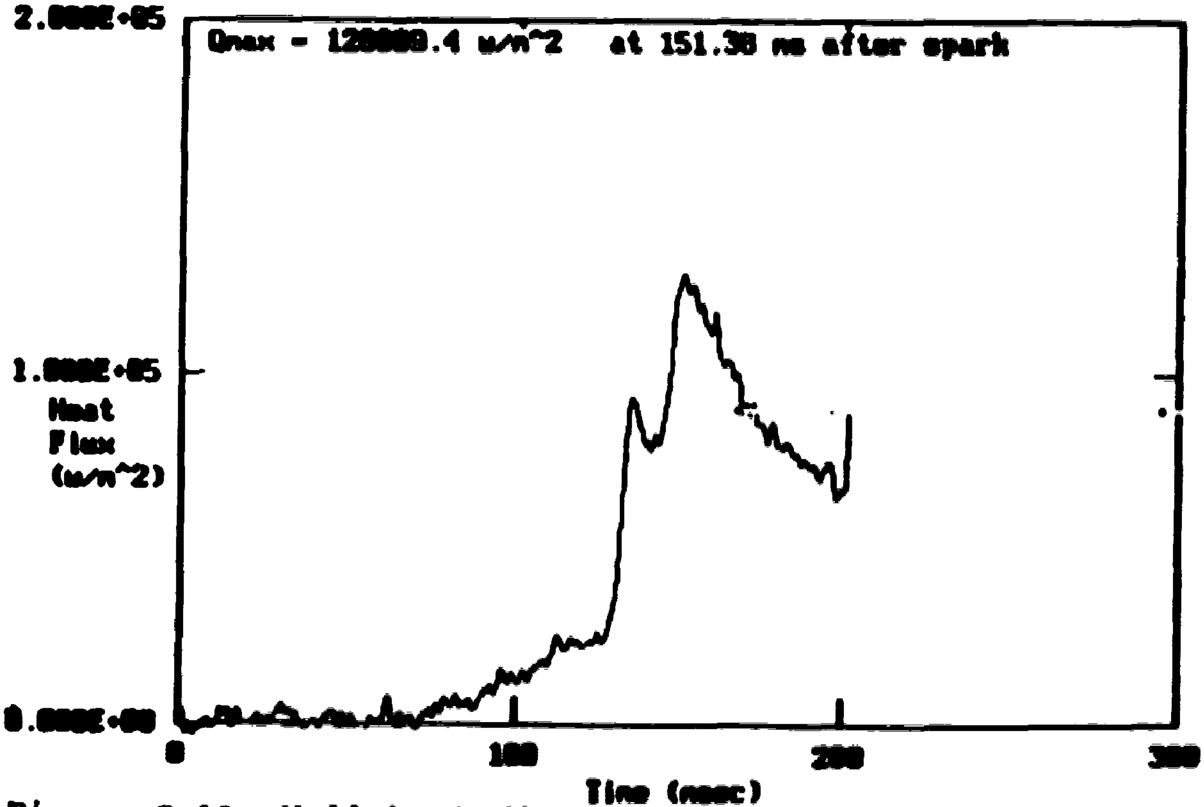

Figure C-12 Wall heat flux variation with time; initial turbulence intensity 1.0 m/s; P_{init} = 1 atm; equivalence ratio 0.6.

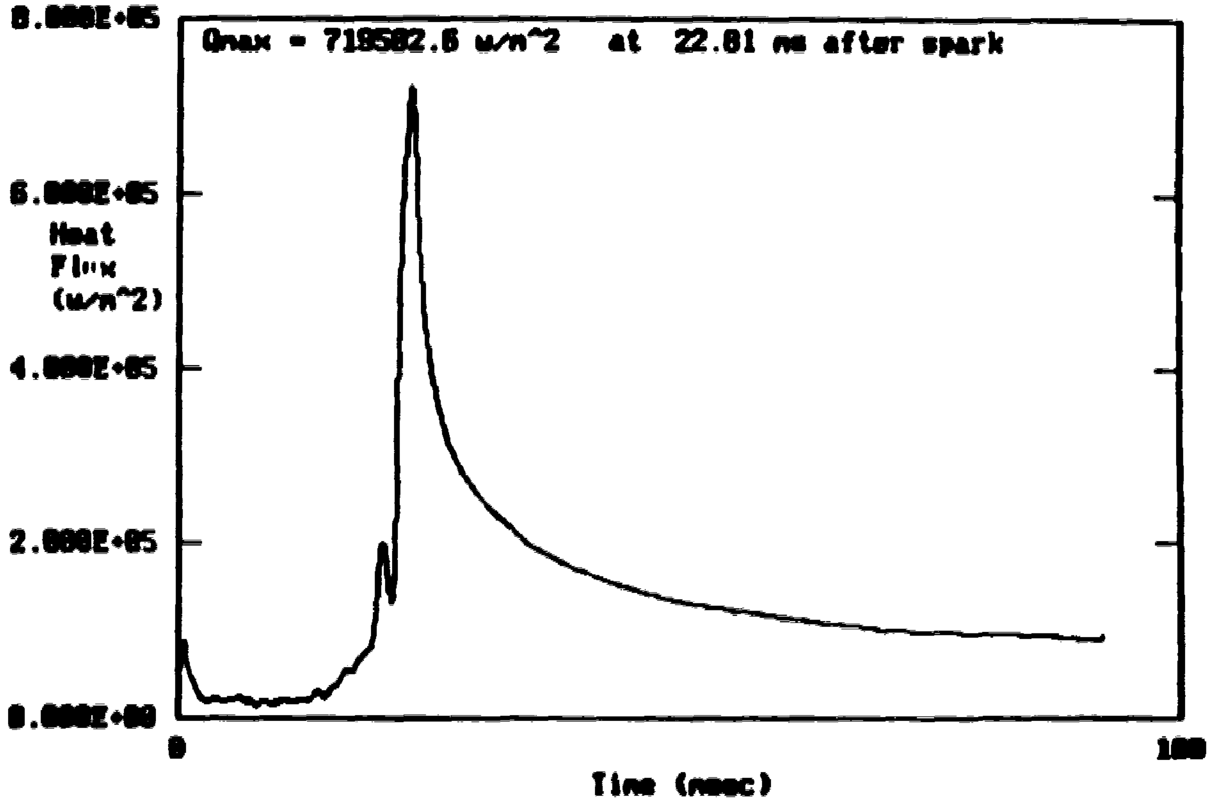

Figure C-13 Wall heat flux variation with time; initial turbulence intensity 1.5 m/s; P_{init} = 1 atm; equivalence ratio 1.0.

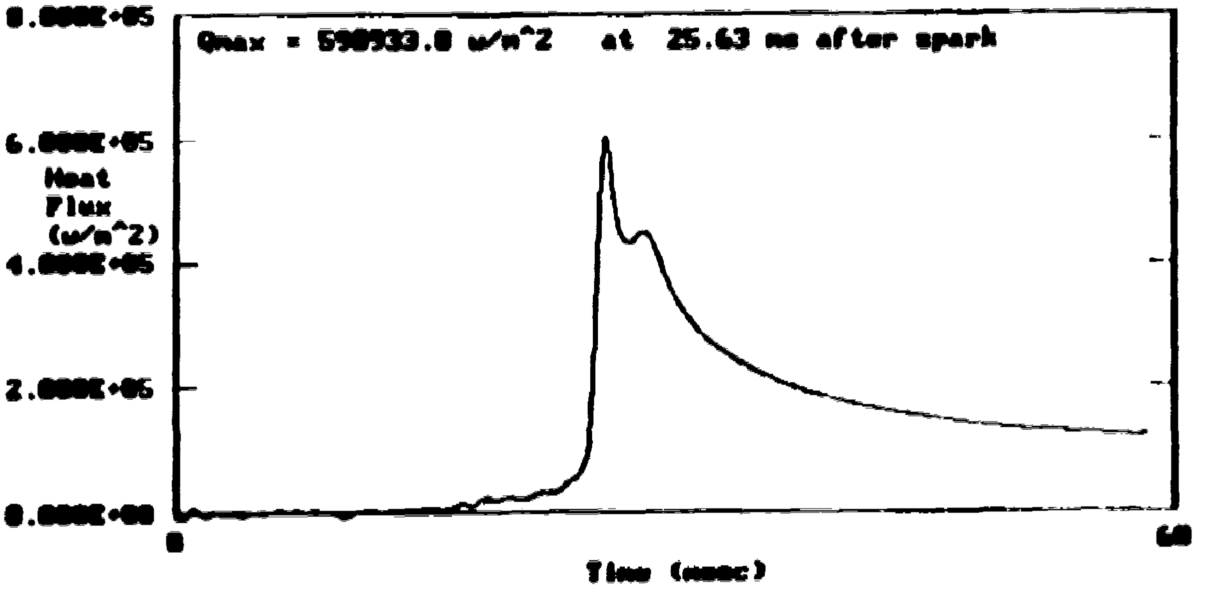

Figure C-14 Wall heat flux variation with time; initial turbulence intensity 1.5 m/s; P_{init} = 1 atm; equivalence ratio 0.85.

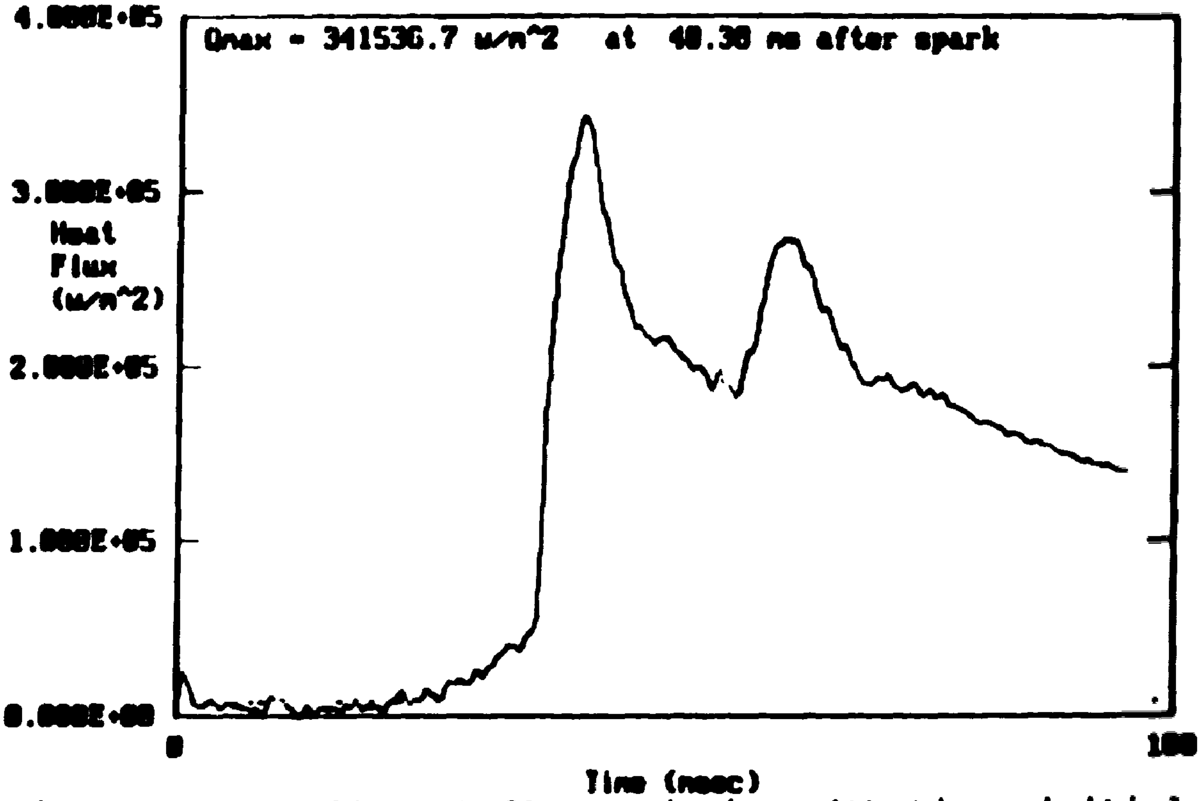

Figure C-15 Wall heat flux variation with time; initial turbulence intensity 1.5 m/s; P_{init} = 1 atm; equivalence ratio 0.75.

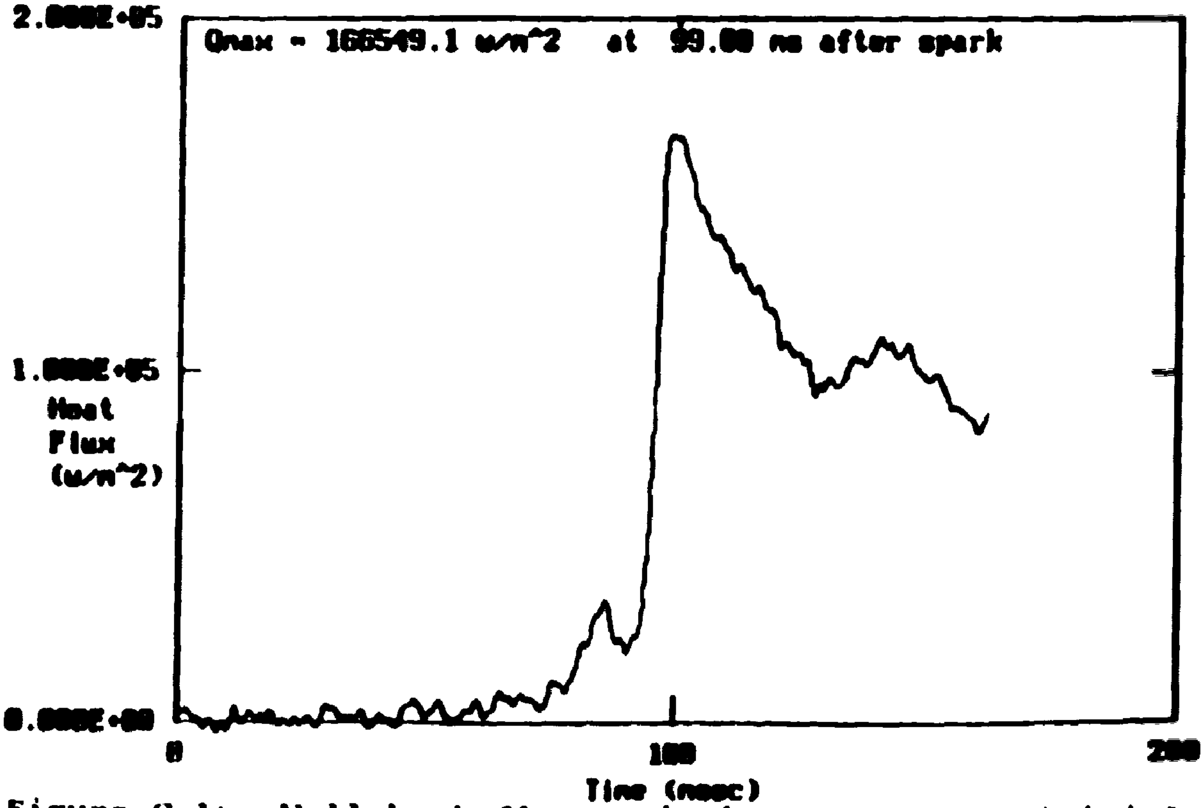

Figure C-16 Wall heat flux variation with time; initial turbulence intensity 1.5 m/s; P_{init} = 1 atm; equivalence ratio 0.6.

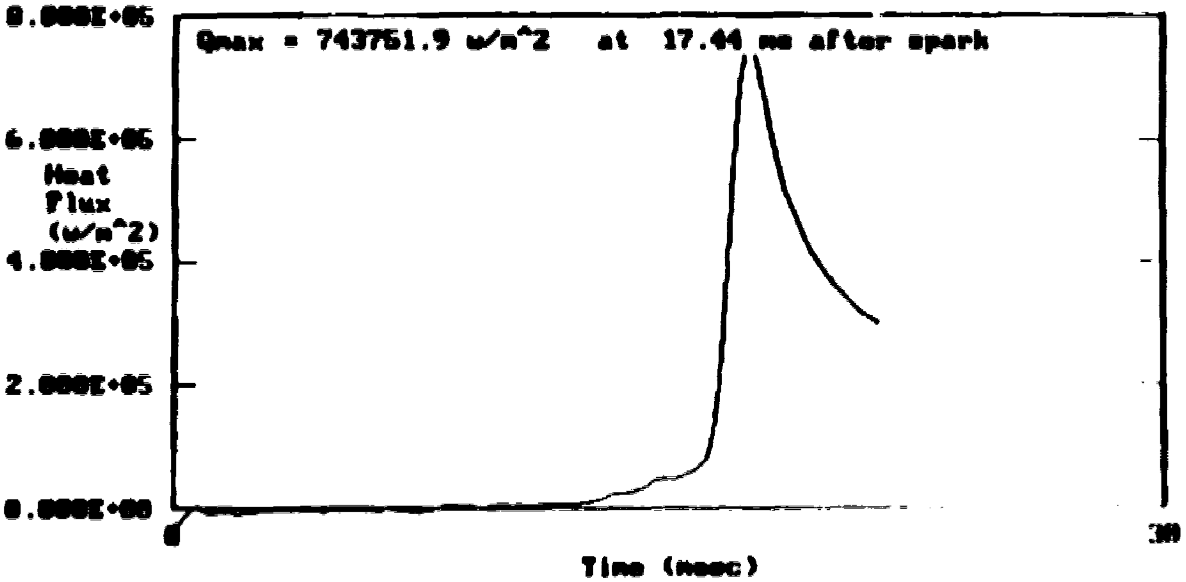

Figure C-17 Wall heat flux variation with time; initial turbulence intensity 2.0 m/s; P_{init} = 1 atm; equivalence ratio 1.0.

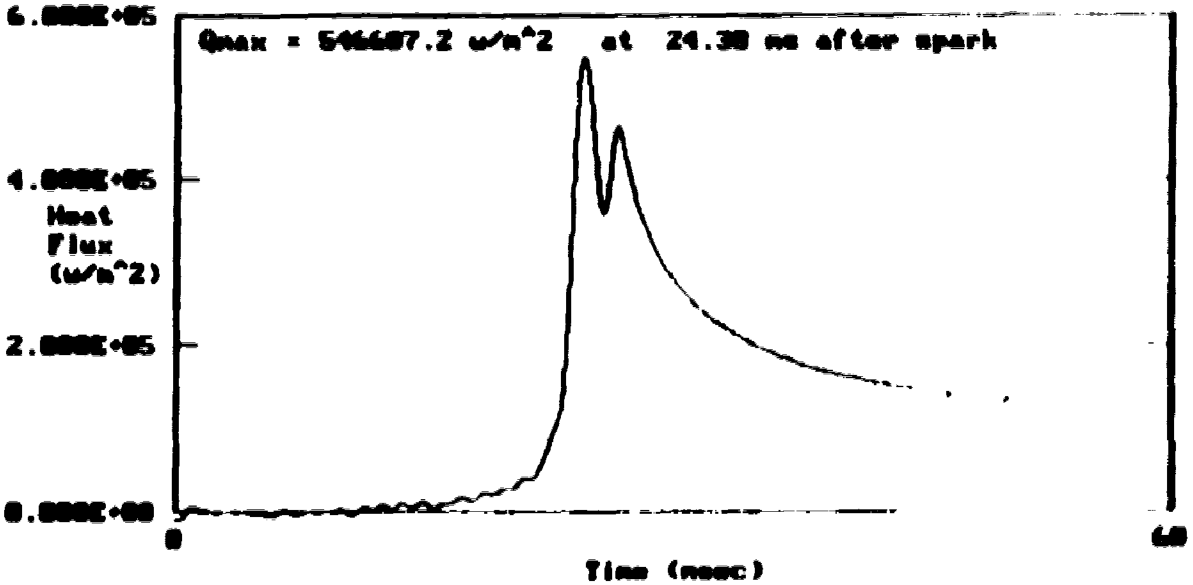

Figure C-18 Wall heat flux variation with time; initial turbulence intensity 2.0 m/s; P_{init} 1 atm; equivalence ratio 0.85.

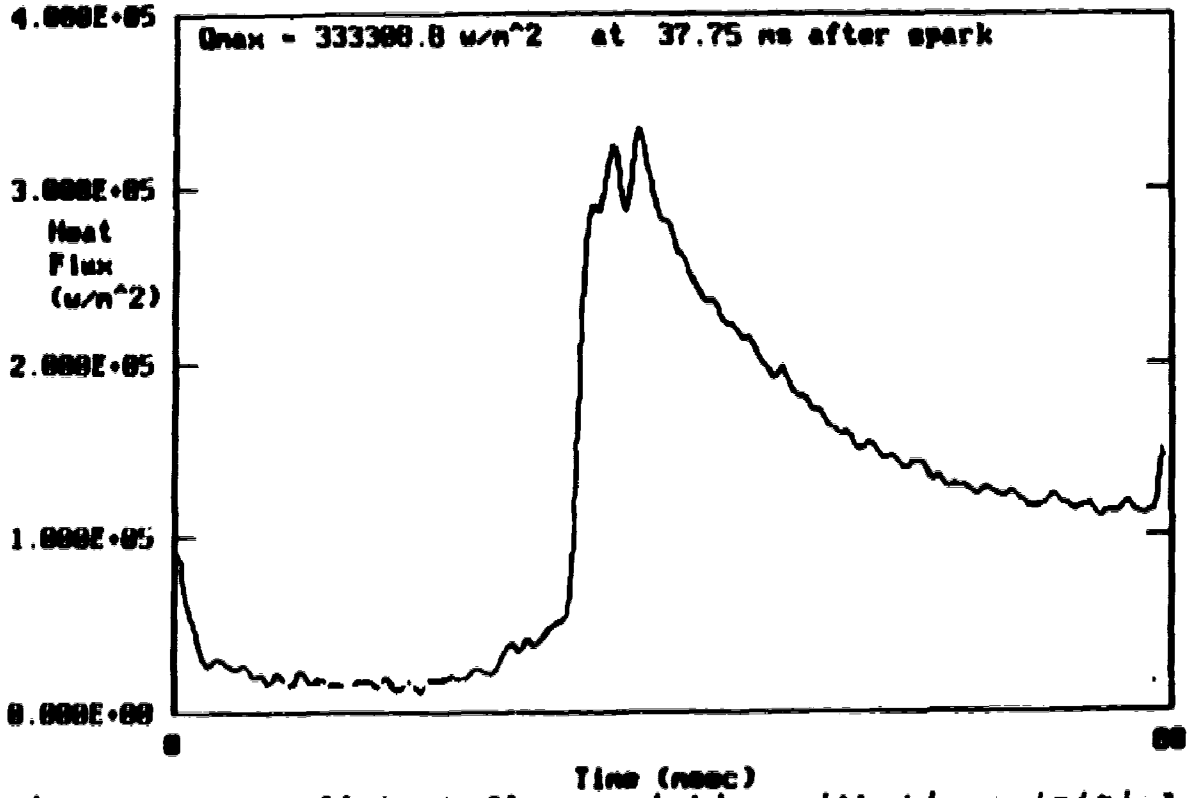

Figure C-19 Wall heat flux variation with time; initial turbulence intensity 2.0 m/s; P_{init} = 1 atm; equivalence ratio 0.75.

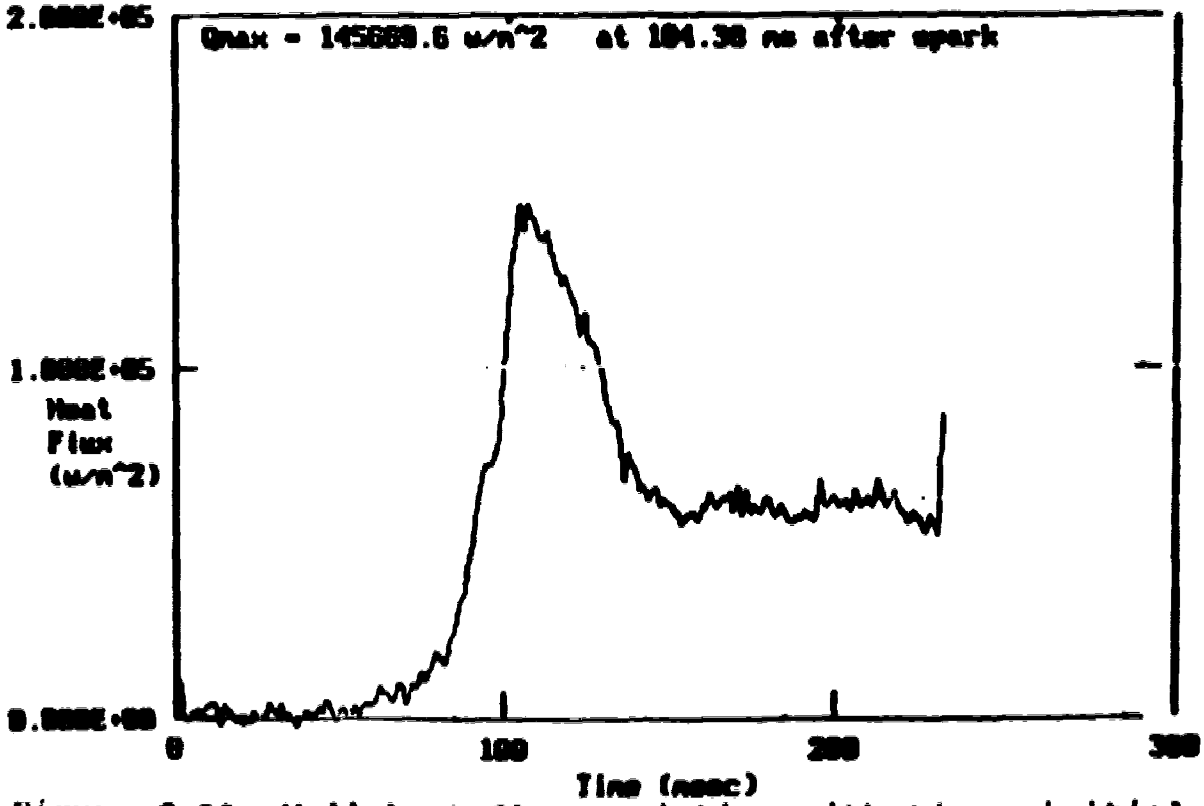

Figure C-20 Wall heat flux variation with time; initial turbulence intensity 2.0 m/s; P_{init} = 1 atm; equivalence ratio 0.6.

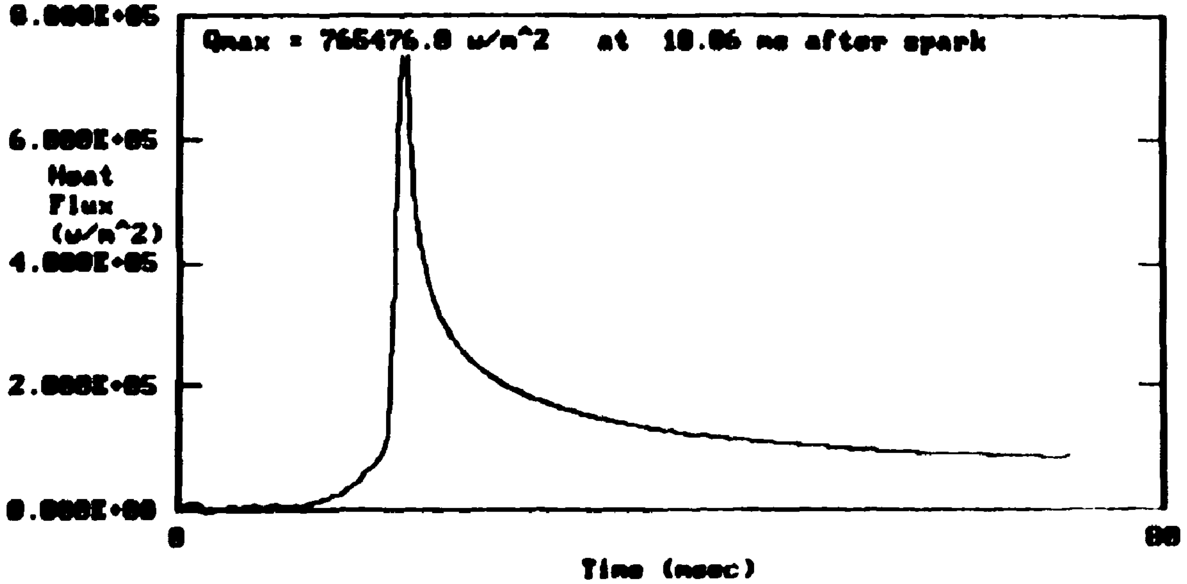

Figure C-21 Wall heat flux variation with time; initial turbulence intensity 2.5 m/s; P_{init} = 1 atm; equivalence ratio 1.0.

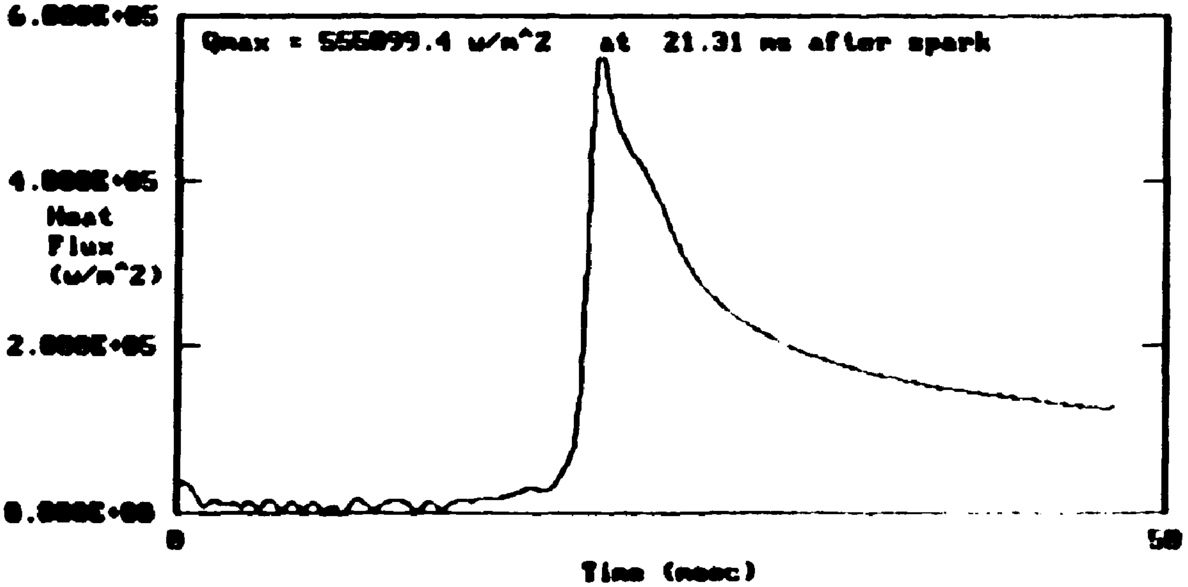

Figure C-22 Wall heat flux variation with time; initial turbulence intensity 2.5 m/s; P_{init} = 1 atm; equivalence ratio 0.85.

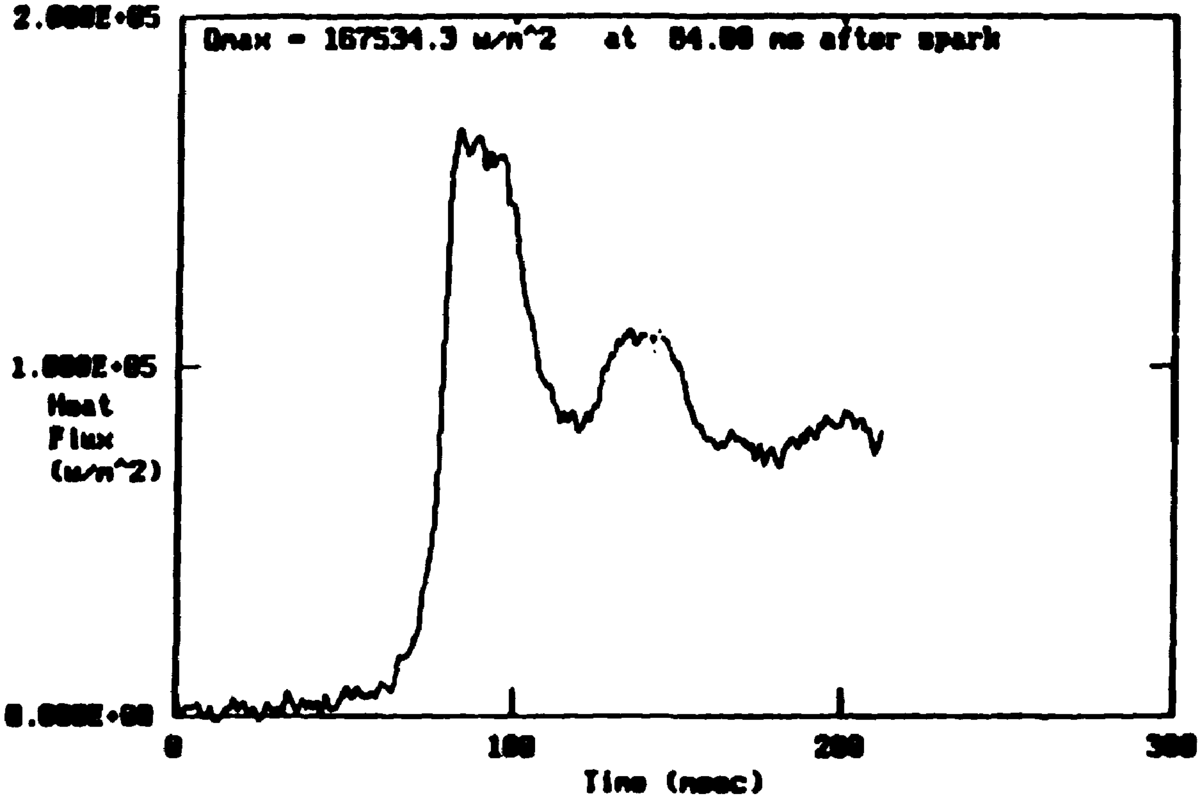

Figure C-23 Wall heat flux variation with time; initial turbulence intensity 2.5 m/s; P_{init} = 1 atm; equivalence ratio 0.6.

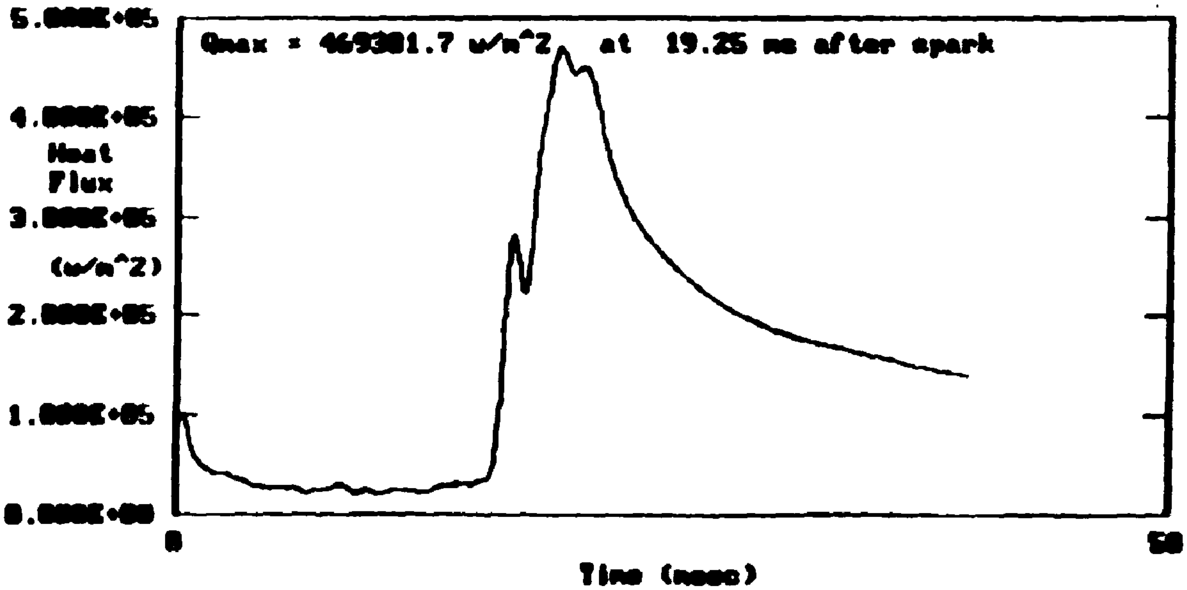

Figure C-24 Wall heat flux variation with time; initial turbulence intensity 3.0 m/s; P_{init} = 1 atm; equivalence ratio 0.85.

APPENDIX D

The remaining heat transfer correlations.

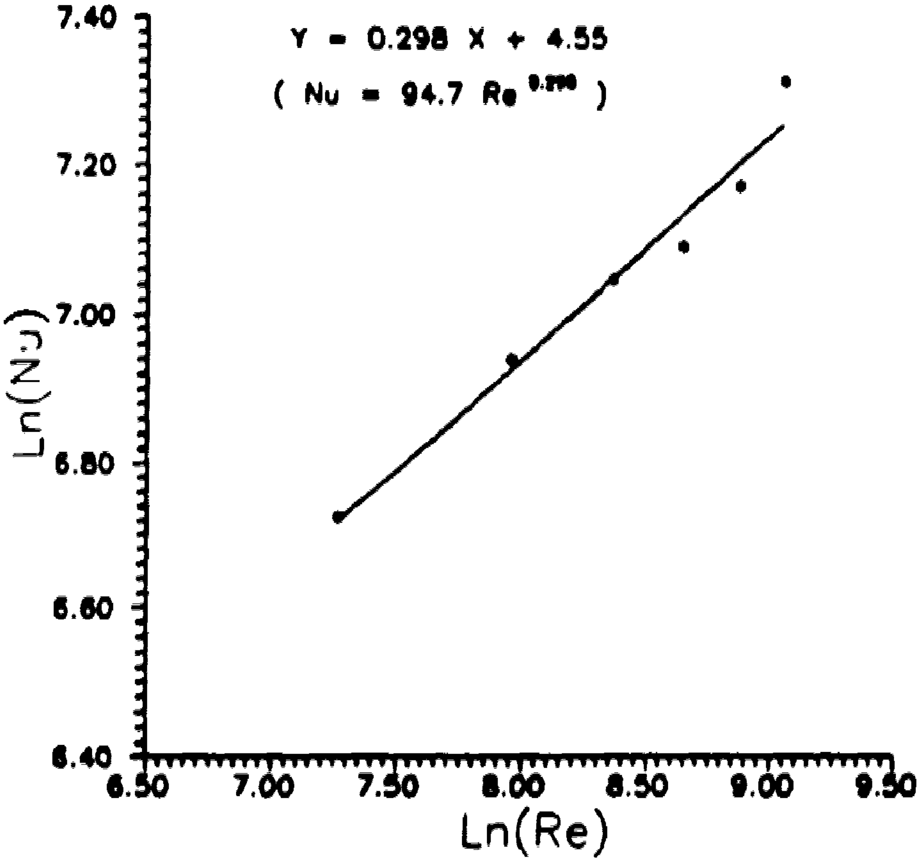

Figure D.1 Wall heat transfer for turbulent combustion in a cubical cell before flames contacting with walls; equivalence ratio 0.85; P_{init} = 1 atm.

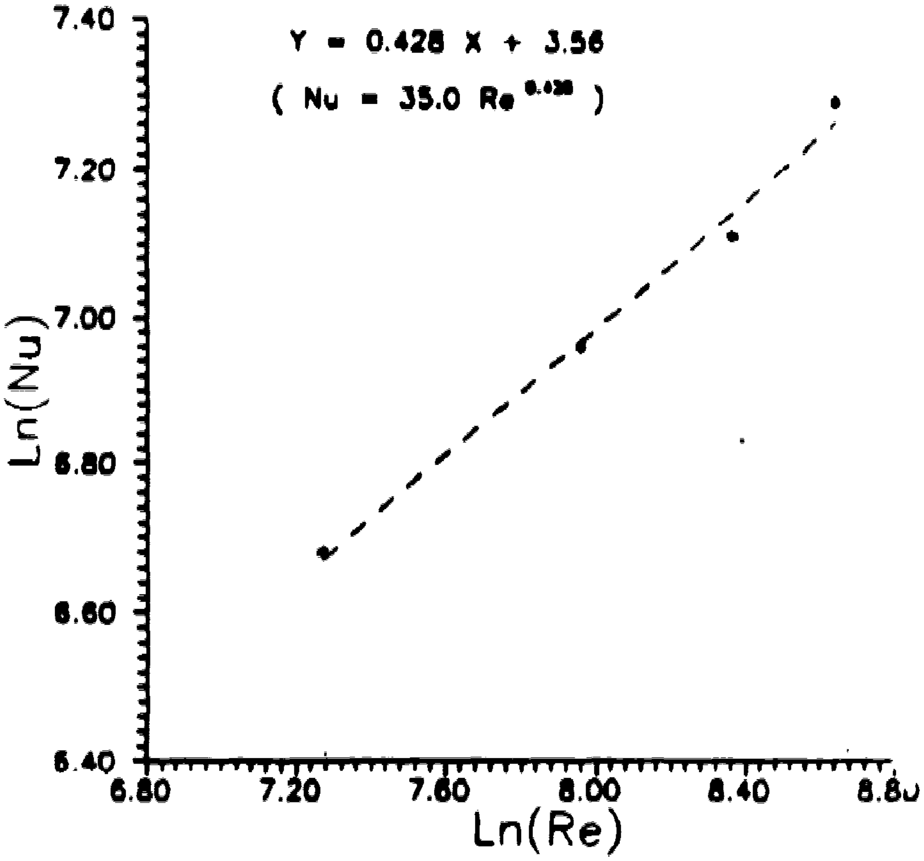

Figure D.2 Wall heat transfer for turbulent combustion in a cubical cell before flames contacting with walls; equivalence ratio 0.75; P_{init} = 1 atm.