AN OVERVIEW OF HEAT TRANSFER FOR PROCESSING THERMOPLASTIC COMPOSITES IN AUTOCLAVES

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NOMENCLATURE

A	=	area, m^2
C_p	=	specific heat of plate, J/kg.K
F	=	view factor
h	=	convection coefficient on mould layup surface, $W/m^2.K$
J	=	radiosity of surface, W/m^2
L	=	length of support rail, 1.0m
m	=	mass of plate, kg
N	=	number of surfaces within enclosure
q_{conv}	=	convection heat transfer rate, W
q_{rad}	=	radiation heat transfer rate, W
q_{tot}	=	total heat transfer rate, W
T_{air}	=	autoclave air temperature measured by permanent autoclave thermocouple, °C
T_p	=	average experimental plate temperature, °C
ϵ	=	emmissivity of surface
x	=	distance from door of autoclave, m

Subscripts

i	=	surfaces i
j	=	surface j
conv	=	convection
p	=	plate
rad	=	radiation
sw	=	side wall
dp	=	duct plate
dr	=	door
he	=	heat exchanger

ABSTRACT

One of the obstacles to the commercial viability of the diaphragm forming of thermoplastic composite components is the length of the process cycle. Most of the process cycle time is required for heating and cooling of the mould and layup. This paper deals with a preliminary analysis of the heat transfer within an autoclave to moulds and layups and through a mould and layup, used in the diaphragm forming technique. The aim of the paper is to determine the relative importance of the various thermal resistances and energy flows in the manufacturing process. The results of this study are to be used in the planning of a more detailed and long-term experimental and computational research program on the process.

The heat transfer analysis is carried out on the autoclave by performing simple experiments to determine the importance of the different modes of heat transfer. Brass plates with high and low emmissivities are used to determine the convection and radiation energy balance to mould surfaces within the autoclave. A simple model is also developed to model the radiation and convection heat transfer to the surface of a flat plate within the autoclave.

The results show that the convection coefficient within the autoclave does not vary substantially along the centre-line of the UCG autoclave. The total radiation heat transfer to a plate with a surface emmissivity of 0.95 is between 45% and 57% of the total heat transfer, during a preheat cycle during the initial five minutes of heating. The external and internal resistances to heat transfer for a mould and layup are both important during the process. Thermal resistances within the plies of the layup are a substantial component of the overall thermal resistance.

1. INTRODUCTION

During the last decade the arrival of a new generation of high performance thermoplastic composites has stimulated the development of manufacturing processes for these new materials. The manufacturing methods for high performance fibre reinforced composites have already been developed mainly for thermoset matrix materials. The main manufacturing techniques for both thermoset and thermoplastic composite materials are bag moulding, pultrusion, thermoforming and injection moulding. Research at the Department of Mechanical Engineering at University College, Galway [1,2] has concentrated on the forming of thermoplastic composite materials using diaphragm forming techniques within an autoclave. Diaphragm forming techniques within an autoclave are relatively new and require substantial development and research to make them both technically and commercially viable.

Most composites processing techniques to-date rely on a limited data base generated over the years through expensive and time comsuming experiments. The trial-and-error approach adopted gives little understanding of the various parameters involved in the process. These factors contribute to the current high cost of composites [3]. One of the obstacles to the commercial viability of diaphragm forming techniques is the length of the process cycle times. The majority of this process cycle time is used in the heating and cooling of the mould and layup. As a first step in the reduction in the heating and cooling time, the flow field within autoclaves and the heat transfer characteristics of autoclaves, moulds and layups must be fully understood. A full understanding of the heat transfer characteristics of autoclaves and diaphragm forming techniques will not only lead to improved cycle times but also to the prediction of the physical and mechanical properties of thermoplastic composite components. Research carried out by Ogale and McCullough [4] show that the actual physical and mechanical properties of the thermoplastic composite are influenced by the cooling rates of the parts during processing. Ogale and McCullough [5] also show that the physical aging characteristics are related to the cooling rate. O' Bradaigh and Mallon [6] have shown that processing composite materials at temperatures outside the optimum process temperature range also significantly affects the mechanical and physical properties of the end product. This paper deals with experimentally investigating the heat transfer within the UCG autoclave to moulds and layups and the subsequent heat transfer through the mould and layup.

In spite of its importance, very little research has been carried out on the heat transfer in autoclaves. Ghariban, Haji-Sheikh and Lou [7] have measured the convection heat transfer coefficients over a flat plate within a scaled down physical model of a concentric cylinder autoclave. They show that the ratio of the experimentally measured convection coefficients to that theoretically predicted, varies from near 3 at the entrance region to 1 downstream within the model autoclave. They also measured the local velocities and turbulence levels using three-channel hot-wire anemometry. and show that the turbulence levels were very high along the entire length of the model autoclave. Murphy [2] shows that an overall surface heat transfer coefficient of $60 W/m^2.K$ models the heat-up curves of various moulds and layups within the UCG autoclave. He modelled the heat transfer through the mould and layup as a 1-D problem, using finite element analysis (FEA). The overall surface heat transfer coefficient is determined using trial-and-error by comparing the temperature against time from FEA results with experimental results.

In his general review of the subject Guceri [3] summarises the role of the thermal engineer by stating, 'In thermoplastic-matrix composites the single most important factor, therefore, becomes the rate of application and subsequent removal of heat from the composite'.

2. OBJECTIVES AND APPROACH OF THIS PAPER

Murphy [2] and Ghariban et al. [7] do not attempt to determine the relative importance of the different modes of heat transfer within autoclaves. Ghariban et al. [7] analyse thoroughly the convection heat transfer within a physical model of a typical autoclave. The autoclave air and wall temperatures are at ambient temperatures. The convections coefficients over a hot flat plate at different locations, within the autoclave, are determined by cooling the hot plate with the cooler air circulating over the plate. Any radiation heat transfer from the plate is treated as a heat loss and is assumed to be constant. Murphy [2] determines an overall heat transfer coefficient to the top and bottom surfaces of the mould and layup, but no attempt is made to distinguish between the convection and radiation heat transfer. Murphy's [2] results are based entirely on analytical methods and no direct measurements of the surface heat transfer coefficients have been made. This paper attempts to establish the relative importance of the different modes of heat transfer within autoclaves. The long term objectives of a 4-year project undertaken by the authors of this paper are:

1. Develop a complete understanding of the heat transfer mechanisms involved in diaphragm forming within autoclaves in general.
2. Develop a model to predict the heat transfer to different moulds and layups within different autoclaves.
3. Use the model to determine modifications which can be made within autoclaves and to moulds to improve the heat transfer during the diaphragm forming process.
4. Develop a computer model to assist design and process engineers in making decisions which maximize heat transfer and minimize the process cycle times.

The approach taken in this paper is: (a) to experimentally measure the heat transfer coefficients over a flat plate at different locations within the UCG autoclave, (b) record the heat-up times for low and high emmissivity flat plates heated within the autoclave and (c) model both the radiation and convection heat transfer to these flat plates and compare to experimental results.

The aims of this paper are (a) to estimate the energy flows to moulds within the UCG autoclave and (b) to estimate the thermal resistances to heat transfer through a mould and layup. The relative importance of the different modes of heat transfer is then established.

3. AUTOCLAVES AND DIAPHRAGM FORMING

Autoclaves are commercially available in a wide range of internal geometries and sizes and are usually built to suit a customer's needs. The interior structures, heating, cooling and control systems also vary with the different manufacturers.

3.1 Description of UCG Experimental Autoclave.

The UCG experimental autoclave was designed and assembled in the Mechanical Engineering Department at UCG. The major engineering work was contracted out, while the assembly and light engineering, including circuit manufacture, was carried out on site [1].

The autoclave (see Fig. 1) consists of a pressure vessel, designed and constructed to BS5500 standards with a maximum design pressure of 2.06MPa. The heating system consists of 3 band heaters with a total power output of 36kW. The heater bands cover the entire outer surface of the central steel cylindrical sleeve. The vessel is insulated by wrapping insulation around the outer surface of the heater bands. Insulation is also packed into the end and door region.

A fan is built into the back end of the autoclave to circulate the gas (air/nitrogen) through the ducts at the top and bottom of the vessel and back down the centre channel. The mean air velocity through the working section of the autoclave has been measured to be approximately 0.5m/s. The cooling system consists of a water cooled heat exchanger consisting of 4 rows of 12.5mm outer diameter tubes in a staggered arrangement with 56 tubes in total. The door opens horizontally from the autoclave by sliding it in and out from the vessel and is closed by bolting to the vessel. The pressurisation is achieved by cylinders of compressed nitrogen gas. The moulds are supported on two rails bolted perpendicularly to the door.

The temperature is recorded using type K thermocouples which have a maximum operating temperature of 1300°C and an accuracy of +/- 3°C at 400°C. Two permanent thermocouples are fitted within the autoclave in order to control the autoclave air temperature. One thermocouple is attached to the autoclave inner side wall (see Fig. 1) to record the side wall temperature. The second thermocouple is sheathed, to measure and record the air temperature as positioned in Fig. 1. Ten thermocouples fabricated from type K thermocouple extension cable are used to measure the temperature of the moulds etc. during processing. These thermocouples access the autoclave through the door.

An IBM PC is used to carry out the control and data acquisition during processing. PID control techniques are used to control the autoclave air temperature. The temperature and pressure measurements are sampled and displayed on the PC screen every 20 seconds and the data acquisition software writes the temperature and pressure measurements to a data file every 60 seconds.

3.2 Diaphragm Forming in an Autoclave

Figure 2(a) shows an exploded view of a mould and layup assembly used in the diaphragm forming process. In diaphragm forming in an autoclave, the unconsolidated composite plies and a vacuum ring are held between two thin plastically deformable sheets known as diaphragms, which may be metallic or polymeric. The diaphragms are clamped to the mould and the air is evacuated from between them using a vacuum pump. The entire assembly is heated in the autoclave to the composite processing temperature and formed, under pressure, into the mould shape (see Fig. 2(b)). The formed part is then cooled under pressure past the transition temperature of the matrix material, before the pressure is removed.

Figure 3 shows a schematic of a typical process cycle for APC-2, an ICI plc. product. At present, cycle times are in the range of 30-60 minutes. Unlike thermosets, thermoplastics do not have to be cured for long periods at different temperatures and can be heated rapidly to the processing temperature. The mould and layup may be either heated from ambient temperature along with the autoclave (non-preheat cycle) or by heating within a preheated autoclave. In the latter case, the door of the autoclave is left open and the autoclave is heated to the processing temperature with a 'thermal plug' placed in the entrance. The thermal plug consists of circular plate 25mm thick which fits snugly into the entrance of the autoclave.

4.UCG AUTOCLAVE HEAT TRANSFER

This section describes the different modes of heat transfer that are used in the diaphragm forming process of thermoplastic components within an autoclave.

4.1 Heat Transfer within the Autoclave

The heat transfer mechanism to a mould and layup within an autoclave are:

1. Radiation heat transfer from the interior surfaces of the autoclave. The UCG autoclave has six radiating surfaces (see Fig. 1) consisting of:
   1. Left side wall.
   2. Right side wall.
   3. Top duct plate.
   4. Bottom duct plate.
   5. Heat exchanger.
   6. Door.

2. Forced convection heat transfer from the air circulating through the autoclave working section.

In the UCG autoclave the temperature reading of the side wall thermocouple is used to control of the autoclave air temperature. In order to achieve the required air processing temperature quickly, the control system allows the side wall temperature to overshoot it's steady state temperature. As the air approaches the required temperature, the control system switches the heaters off and on for calculated time periods until steady state conditions exist. During the processing of APC-2 (380°C), the side wall temperature may reach temperatures of 450°C and are usually between 400°C-410°C for steady-state conditions during the APC-2 process cycle.

The top duct plate temperature was measured close to the entrance region and also above the air thermocouple position (see Fig. 1). The duct plate temperature heated up slower than the air temperature. During steady-state conditions the temperature at the mid-length was 10°C greater than the air temperature. The thermocouple reading close to the door was an average of 10°C below the air temperature. No direct measurement of the heat exchanger temperature was carried out but it may be assumed to be the same as the air temperature due to the air circulating around the tubes which are drained during heating. The door is the slowest surface to heat up. During preheat process cycles the door with mould mounted on the rails is kept open so that both door and mould have to be heated together, from ambient temperature, by both radiation and convection heat transfer.

All the interior surfaces including the heat exchanger are made from mild steel and have heavily oxidised surfaces (rust) due to long term use. Oxidised steels have high emmissivity (0.66 - 0.81 [8]) values and are therefore very efficient at emitting radiant heat. Moulds are usually made of stainless steels which have low emmissivity values (0.16 -0.24 [8]) and the top of the layup is a diaphragm material (polymeric or metallic) which may be either transparent (Uplilex) or opaque (Aluminium).

The forced convection heat transfer to a mould and layup within the autoclave is achieved by the hot air circulated by the fan over the surfaces of the mould and layup. The convection heat transfer is going to be greater during a preheat cycle than a non-preheat process cycle due to the greater temperature differences between air, mould and layup surfaces. The measurement of convection coefficients over the surfaces may be achieved easily for moulds of simple geometries but becomes more difficult as the mould geometries become more complex.

4.2 Heat Transfer Through Mould and Layup.

The following is a summary of the heat transfer mechanisms through the mould and layup (see Fig 4) which consists of:

1. Conduction heat transfer through the diaphragms, composite prepreg, air gaps and mould materials.
2. Heat transfer across contact resistances between the various plies within the layup.
3. Natural convection within the enclosure between the inside of mould and bottom diaphragm.
4. Radiation across the air gap between the inside of the mould and the bottom diaphragms.

Conduction heat transfer through the diaphragms, mould and air gap can be analysed using analytical methods. Conduction through the prepreg is made complex by the rapidly changing state of the prepreg as it melts. The contact resistances across the plies is pressure sensitive and will also change during heating as the prepreg softens and melts. Natural convection within the enclosure will vary from mould to mould. It may be ignored within long flat moulds as the depth of the air gap will be small compared to it's length and no recirculation of air will occur. However as the mould geometry becomes more complex the air gaps will increase and the natural convection will become more important. The importance of radiation heat transfer across the air gap will depend on the size of the temperature difference and emmissivities of the mould and diaphragm surfaces.

5. EXPERIMENTAL AND MODELLING APPROACH

The experimental work for this paper is carried out in two stages to approximately estimate:

1. Heat transfer and energy flows to a mould and layup within the UCG autoclave.
2. Heat transfer and thermal resistances through the typical mould and layup materials.

.5.1 Heat Transfer to the Mould

The steps in the experimental approach to analyse the heat transfer to a mould within the UCG autoclave are:

1. Record the heat-up of a low emmissivity (polished) plate within a non-preheated autoclave.
   Objective: To estimate the convection coefficient (h) for a flat plate at different position on the centre-line of the autoclave.
2. Record the heat-up time for a low emmissivity plate, assuming radiation heat transfer to be insignificant, within a preheated autoclave.
   Objective: To demonstrate the reliability of the experimentally determined convection coefficients.
3. Record the heat up of a high emmissivity (black) plate within a preheated and unpreheated autoclave.
   Objectives:
   (i) To directly compare experimental results for low emmissivity and high emmissivity plates
   (ii) to provide an estimate of the radiation contribution to heat transfer
   (iii) to compare experimental results with model results to demonstrate that the estimated convection coefficient and radiation model are realistic.

The convection coefficients can be determined from the experimental results of step 1 and using the following equation assuming the heat transfer to this plate is by convection alone,

$$mc_p dT_p/dt = hA_p(T_{air} - T_p) \quad (1)$$

The temperature difference (T_{air} - T_p) and dT_p/dt are determined from the experimental results of step 1. The experiments of step 2 are used to determine the convection heat transfer to the plate within a preheated autoclave. The experimental results of step 2 are then used to check the accuracy of the model, and the calculated convection coefficients of step 1.

The high emmissivity plate experiments are used to highlight the radiation heat transfer within the UCG autoclave. By using a plate with a high emmissivity surface but with the same dimensions and thermal properties as the low emmissivity plate, the results can be compared directly by comparing the heat-up curves for the two plates. The model is then tested to estimate the radiation heat transfer to the high emmissivity plate. The model and experimental results are compared to determine if the modelling approach is realistic. The calculated convection coefficients are again used in the model to estimate the convection heat transfer to the high emmissivity plate.

The experimental plates (see Fig. 5) are manufactured from brass. The dimensions of both plates are 350mm wide x 140mm long and 1.5mm thick. The dimensions were chosen so that the plate could rest on the existing support rails of the autoclave. The original surface of the brass is highly polished and provides the low emmissivity surface for the first plate. The emmissivity of brass ranges from 0.028 for a highly polished surface to 0.09 for a polished surface (Siegel and Howell, [8]). The high emmissivity surface is obtained by treating the surface with a thin layer of carbon (lampsoot). The emmissivity for carbon is 0.95 [8]. The mass and specific heat of the plates are 0.636kg and 380J/kg.K respectively.

The plate temperature is measured by three thermocouples placed equidistant across the width of the plate (see Fig. 5). The thermocouples are attached to the bottom surface of the plate which is insulated. It is experimentally found that there is a temperature distribution across the width of the plate probably caused by the increased radiation heat to the plates outer edges. The average plate temperature is obtained by averaging the temperature distribution across the width of the plate. By assuming that the temperature distribution is linear from the centre of the plate to the outer edges, the temperature at the edge is obtained and then the average is calculated across half of the plate. The average for the other half is obtained in the same manner. The average temperature of the plate is the average of the temperatures of the two halves. The temperature distribution through the thickness of the plate is assumed uniform because the Biot number for the plate is much less than 0.1 [9] (Biot No. = 1.4×10^{-4}, based on $h=10W/m^2.K$, $L_c=1.5mm$ and $k=110W/m.K$). The door, side wall and air temperatures are measured and recorded during all experiments (see Fig. 1).

5.2 Heat Transfer Through the Mould and Layup

The experimental approach to estimate the important issues in heat transfer through a mould and layup is as follows:

1. Record the temperatures against time for the different layers of a mould and typical layup within a non-preheated autoclave.
   Objective(s): To estimate the relative importance of the different resistances to heat transfer within the mould materials and to compare these to the heat transfer resistances to the outside of mould and layup.
2. Record the temperatures against time for the different layers of the same mould and lay-up which has partly consolidated from the previous run.
   Objective: To demonstrate the relative importance of contact resistances between the unconsolidated plies within the layup.

Diaphragm forming of complex curvature parts has proved successful and various experimental moulds have been designed in UCG. These range from small simple flat plates to 1m wing sections. A female hemispherical mould similar to that in figure 2 is used for the above tests. This mould was chosen because it provides a large air gap of 45mm at the centre axis between the inside of the mould and the bottom of the layup. This large gap was chosen in order to try and maximize the resistance to heat transfer across the air gap. The 2 diaphragms are of Upilex-R material. 24 plies of APC-2, (an ICI plc. product), with a $(0°/90°)_{2s}$ layup are used. APC-2 is a long fibre composite and the fibres are all in the same direction. In the (0°/90°) layup alternate plies are placed at right angles to each other. The 24 plies maximizes the temperature difference between the top and bottom of the layup during heating. The (0°/90°) layup was chosen because the contact resistance between the plies is probably greater than if the carbon fibres in the different plies were running parallel to each other. The temperatures at the top surface of layup, bottom surface of layup, inside of mould and bottom of mould are measured (see Fig. 6). The Thermal conductivities of the different layers in the layup areas follows:

	k (W/m.K)
Upilex-R [2]	0.25
APC-2 [2]	0.74 (20°C)
	0.88 (100°C)
Air Gap [9]	0.0263 (300K)
Stainless Steel [9]	15.0

The thermal resistances from the interior of the autoclave to the mould and layup and the resistances through the mould and layup are calculated using,

$$R_{cond} = L/(kA) \tag{2.a}$$

$$R_{conv} = 1/(hA) \qquad (2.b)$$

$$R_{rad} = 1/(h_{rad}A) \qquad (2.c)$$

where L is the thickness of the layer. The above conductivity values and the thicknesses from Fig. 6 are used in equation 2.

5.3 Experimental Procedure

The following steps are followed for a preheat experiment:

1. Open door fully away from the autoclave and position the experimental plate with thermocouples attached on the support rail.
2. Place thermal plug at the entrance of the autoclave.
3. Switch on heaters.
4. When the autoclave has reached the required temperature (set-point temperature), remove the thermal plug and close the door with the plate in position as quickly as possible.

When carrying out a non-preheat experiment the door with plate in position on the support rails is closed when the autoclave is at ambient temperature and the door, plate and autoclave are heated simultaneously. The set point air temperature for all experiments carried out in this paper is set at 380°C.

The results in the paper presented for the preheat experiments are averaged over the initial 5 minutes of heat-up. This is assuming a linear increase in temperature. The non-preheat results are based on the period from 10 to 20 minutes of heating where the plate, air temperature and side wall temperature increase linearly.

5.4 Error Analysis

An error analysis is carried out on the calculation of the convection coefficient using equation (1). The estimated errors are:

Plate temperature diff. (dT_p)	+/- 2°C (based on 144°C)
Air-plate diff. (T_{air} -T_p)	+/- 10°C (based on 113°C)
Mass of the plate (m)	+/- 0.0001Kg (Based on 0.636kg)
Plate area (A_p)	+/- $4x10^{-6}m^2$ (Based on $0.049m^2$)

The plate temperature difference is based on the 10 minute period, described previously during the non-preheat experiments using the polished brass plate. The error analysis results are for the worst possible case. The accuracy of type K thermocouples is +/-3°C at 400°C. The error estimate for the air - plate difference (T_{air} - T_p) includes any error in the plate temperature due to radiation heat transfer to the polished plate. This error estimate is obtained from the model results assuming the plate has an emmissivity of 0.05. The error is calculated, using addition in quadrature [10], to be 9% for the worst possible case. The average error is 8.5%.

5.5 The Model and Test Approach used in this Paper

This section describes the approach to mathematically modelling the heat transfer to a flat plate within the UCG autoclave as described in the experimental method. The energy balance at the plate is,

$$q_{tot} = q_{conv} + q_{rad} \tag{3}$$

where,

$$q_{tot} = mc_p dT/dt \tag{4}$$

5.4.1 Forced Convection Heat Transfer to Flat Plate

The forced convection heat transfer rate to the plate is,

$$q_{conv} = hA_p(T_{air} - T_p) \tag{5}$$

The convection coefficients (h) over the flat plate could be estimated using correlations such as those found in Incropera and DeWitt [9]. This approach is not feasible within the autoclave as the air velocity over the plate at different locations would have to be known and is beyond the scope of this paper. Using the mean velocity within the centre channel would be also incorrect assuming that the convection coefficient variation along the length of the autoclave is similar to that shown by Ghariban et al. [7]. The convection coefficients used in the model described here are determined experimentally from the low emmissivity plate experiments as described in the experimental approach.

5.5.2 Radiation Heat Transfer

The radiation heat transfer rate to the plate proves to be more complex to solve than the convection heat transfer rate, but can be solved for using analytical methods. The net radiation heat transfer, q_i, from a surface, i, in an N surface enclosure is given by ([9], pp623-679),

$$q_i = \frac{\sigma T_i^4 - J_i}{1-\varepsilon_i/\varepsilon_i A_i} = \sum_{j=1}^{N} \frac{J_i - J_j}{(A_i F_{ij})^{-1}} \tag{6}$$

Figure 7 shows a network representation of equation (6) for the heat transfer between the plate, duct wall and the 2 side walls within the autoclave. To model the heat transfer to the plate, at any position along the centre-line of the autoclave using equation (6), a completely defined enclosure must be specified. Since the bottom surface of the plate is insulated only the surfaces in the top half of the autoclave radiate directly to the top surface of the plate. However the surfaces in the bottom half of the autoclave cannot be ignored as there is radiation exchange between them and the top surfaces of the autoclave. Hypothetical surfaces along the centre-plane of the autoclave must be defined as in Fig. 8(a) to complete the enclosure necessary to use equation (6). There are now ten surfaces (N=10) within the enclosure.

5.5.3 Model Solution Scheme

The temperature of the plate is determined at each time step by rewriting equation 3 as follows,

$$T_p^{n+1} = \frac{q_{tot}\Delta t}{mc_p} + T_p^n \tag{7}$$

where,

$$t = n\Delta t \tag{8}$$

and the integer n is the number of time steps.

The radiation and convection heat transfer are solved for using the temperatures at the previous time (n). The convection heat transfer is calculated using the experimentally measured convection coefficient in the equation (5). The radiation heat transfer is more complex to solve. Equation (6) must be written out for the ten surfaces within the enclosure and then written in matrix form;

$$[A]\{J\} = \{B\} \tag{9}$$

where {J} contains the different surface radiosities terms and may be determined by obtaining $[A]^{-1}$ and solving,

$$\{J\} = [A]^{-1}\{B\} \tag{10}$$

The known temperatures in equation 9 are at time (n). The radiation heat transfer to the plate is then calculated as follows,

$$q_{rad} = \frac{\sigma T_p^4 - J_p}{1 - \varepsilon_p / \varepsilon_p A_p} \tag{11}$$

The view factors (F_{ij}) between the different surfaces are determined using correlations developed by Chekhovskii et al. [11] for parallel and perpendicular plates of arbitrary sizes. To calculate the view factors to the curved side walls using correlations from [11] another hypothetical surface as in Fig. 8(b) is defined.

The side wall, door and air temperatures recorded during the experimental tests are used in the model. The duct plate and heat exchanger temperatures are assumed to be the same as the air temperature. The temperatures of the hypothetical surfaces are also assumed to be the same as the air temperature. The time step (dt) used in the model is 60 seconds because the temperatures are recorded by the data acquisition system every 60 seconds.

6. RESULTS

The results presented in this paper are for the heat transfer analysis carried out on the UCG experimental autoclave. The heat-up rates (C/minute) for the preheat experiments are a linear average over the initial five minutes. The heat transfer rate (W) results for the preheat experiments are based on the average heat-up rate as described. The heat-up rates for the non-preheat experiments are based on the 10-20 minute period of heating where the rise of plate temperature against time is close to linear. The heat transfer rates for the non-preheat experiments are based on this 10-20 minute period.

6.1 Experimental Results for Low and High Emmissivity Plates

The main findings from the heat-up experiments of the two plates are:

1. The average convection coefficient over the plate shows little variation along the centre-line of the autoclave (Figure 9). The large variation in (h) found by Ghariban, Haji-Sheikh and Lou [7] in their model autoclave are not apparent

here. The average coefficient along the centre-line of the UCG autoclave is $10.23W/m^2.K$.

2. The high emmissivity plate heats up faster than the low emmissivity plate during both preheat and non-preheat experimental runs. Figures 10 and 11 show typical results for the low and high emmissivity plates respectively. The heat transfer rate to the plates during preheat experiments, at x=0.575mm, increases from 113W for the polished plate to 270W for the black plate (28°C/minute to 67°C/minute). The average heat transfer rate during non-preheat experiments, increases from 59W to 83W (15°C/minute to 21°C/minute)
3. The black plate heat-up curves shows significant variations from the front (i.e. door end) to the back of the autoclave. Figure 11 shows that, for the high emmissivity plate, the heat-up is significantly slower when the plate is near the autoclave door. It is also clear that with the plate near the door it does not reach the steady-state temperature achieved away from the door. The heat transfer rate for the preheat experiments, increases from 210W at x=0.055mm, to 270W at x=0.575 (52°C/minute to 67°C/minute).
4. The polished plate heat up curves show little variation along the length of the autoclave (figure 10). The average heat transfer rates are 115W and 59W (28.7°C/minute and 14.6°C/minute) for the preheat and non-preheat experiments respectively.

6.2 Mould and Layup Experimental Results

Figure 12 shows the temperature distribution through the mould and layup for the consolidated layup experiment. The temperatures of the inside of the mould and the bottom of the layup are within 2°C of each other. The top of the layup and the outside temperature of the mould are also similar. The main findings from this analysis are:

1. The resistance to heat transfer across the air gap is smaller than expected. The average temperature difference between the inside of the mould and the bottom of the layup is 2°C.
2. The thermal resistance through the consolidated prepreg is only 23.5% of the thermal resistance through the unconsolidated prepreg. This percentage is based on the decrease in temperature difference through the layup observed between the unconsolidated and consolidated layup. The decrease can been observed by comparing figure 12 and 13.
3. The external resistance to heat transfer to the mould from the interior of the autoclave and the resistances through the mould and composite prepreg are both important. This can be observed by the different temperature differences on figure 13.

Based on these results and a study of the expected thermal resistances due to (a) radiation/convection at the surface and (b) conduction through the mould and layup material, it is clear that:

1. Natural convection and long-wave radiation heat transfer in the air gap play significant roles.
2. Thermal resistances between the plies in the layup is a substantial component of overall thermal resistance.

6.3 Model Results

The emmissivities for the polished and black plates are assumed to be 0.05 and 0.95 [8] respectively. The emmissivities of the interior surfaces are all assumed to be 0.81 [8]. The calculated convection coefficient at the different positions along the centre-line of the autoclave are also used in the model. The model reads in the temperatures of the side walls, door and air from the experimental data file. The heat exchanger duct plate and hypothetical surfaces along the centre-plane are assumed to have the same temperatures as the air. Measurement of the duct plate temperature shows the duct plate to be very close to the air temperature.

Figure 14 shows the results of using the model, using $\epsilon=0.05$ for the polished plate in a non-preheated autoclave. The net heat transfer to the plate is over predicted by 6.8%. The percentage differences in heat transfer are based on the experimental results for the 10 to 20 period on the heat-up curves.

Figure 15 shows the results of the model for the black plate at x=0.575mm ($\epsilon=0.95$) in a preheated autoclave. The maximum temperature difference between the experimental and model results in figure 15 is 21°C. The model overestimates the heat transfer rate to the this plate by 6.4%. The model fails to predict the heat-up curve of the black plate at the position closest to the door during a preheat experiment and overestimates the heat transfer rate close to the door by 31%.

Discussion of Results

The lower mean air velocity within the working section of the UCG autoclave or the complexity of the air flow peculiar to each autoclave may explain the small variation in the convection coefficient along the length of the UCG autoclave compared to the results of Ghariban, Haji-Sheikh and Lou [7]. Radiation heat transfer within the UCG autoclave may be somewhat higher than in other autoclaves due to the direct heating of the side walls and the location of the heaters. However, it is clear that the radiation heat transfer to moulds within all autoclaves is a very important mode of heat transfer especially when the autoclave is preheated.

The model results show that the radiation heat transfer may be modelled using analytical methods. The model developed here is for the heat transfer to a simple flat plate heated in the UCG autoclave. The average convection coefficient to this plate may be determined relatively easy by direct measurement. As the mould geometries become more complex the determination or prediction of the convection coefficient will become increasingly more difficult. The cold door reduces the heat transfer to a mould close to it during preheat cycles and methods of counteracting this reduction in heat transfer will have to be investigated.

CONCLUSIONS

1. The heat transfer convection coefficient does not display great variations along the length of the UCG autoclave compared to that of [7].
2. The radiation heat transfer from the interior surfaces within the UCG experimental autoclave is high (between 45%-57% for plate with e=0.95 during preheat cycle and an average of 29% for the non-preheat cycle).
3. Although the analysis carried out in this paper deals with the UCG experimental autoclave, the above results indicate that radiation heat transfer within autoclaves in and to moulds in general cannot be ignored and needs to be further investigated.
4. The external resistance and internal resistances to heat transfer for a mould and layup are both important and need to be further investigated.

ACKNOWLEDGEMENTS

This project was financially assisted by the BRITE program of the Commission of European Communities, Brussels. We would like to thank Prof. P. Mallon, Mr. M. Monaghan of University of Limerick who designed our autoclave at UCG and the technical staff at UCG's Department of Mechanical Engineering. We also like to thank

Prof. P.H. Oosthuizen of Queen's University, Kingston, Canada for his participation in discussions of the methods.

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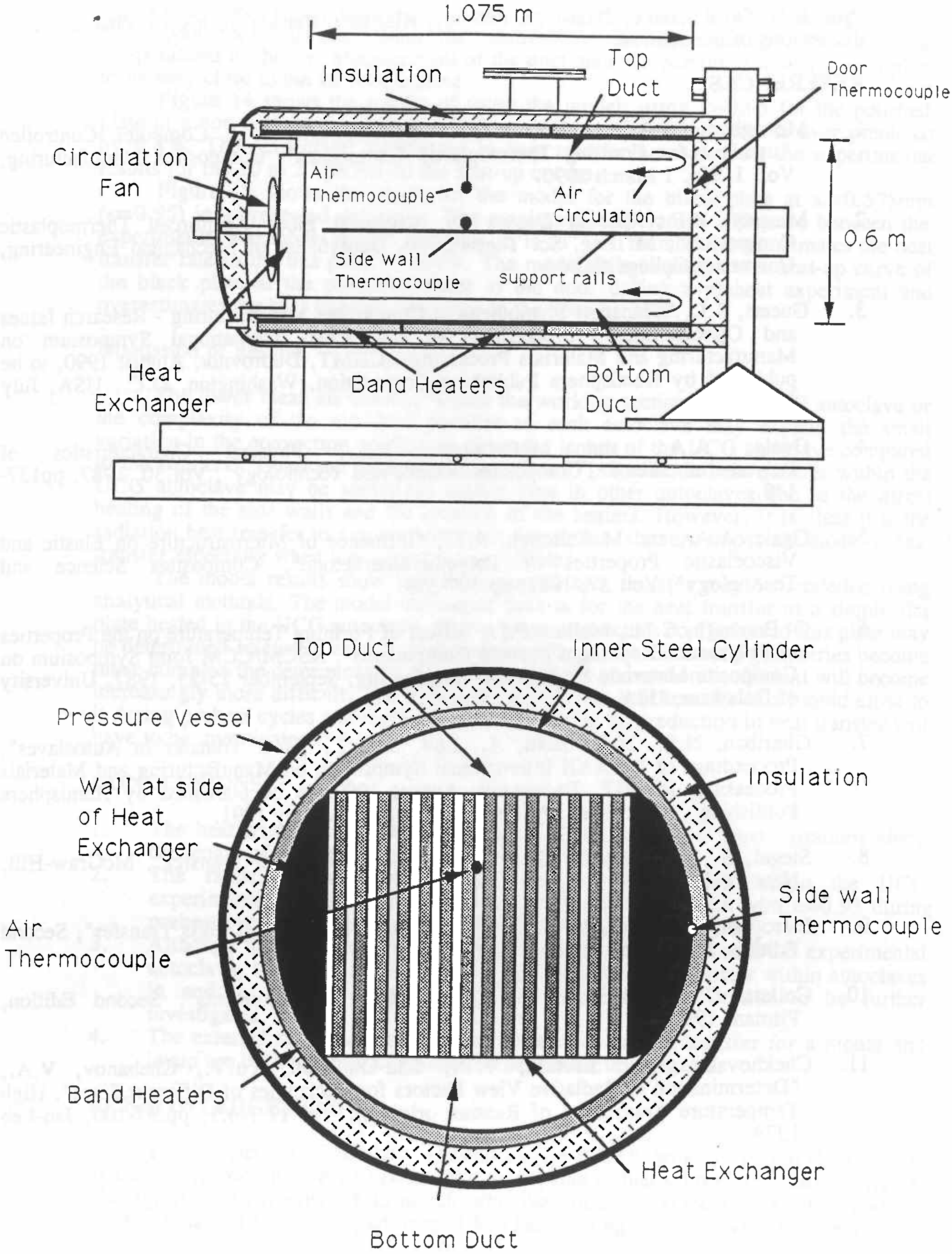

Fig. 1 Diagram of the UCG experimental thermoforming autoclave.

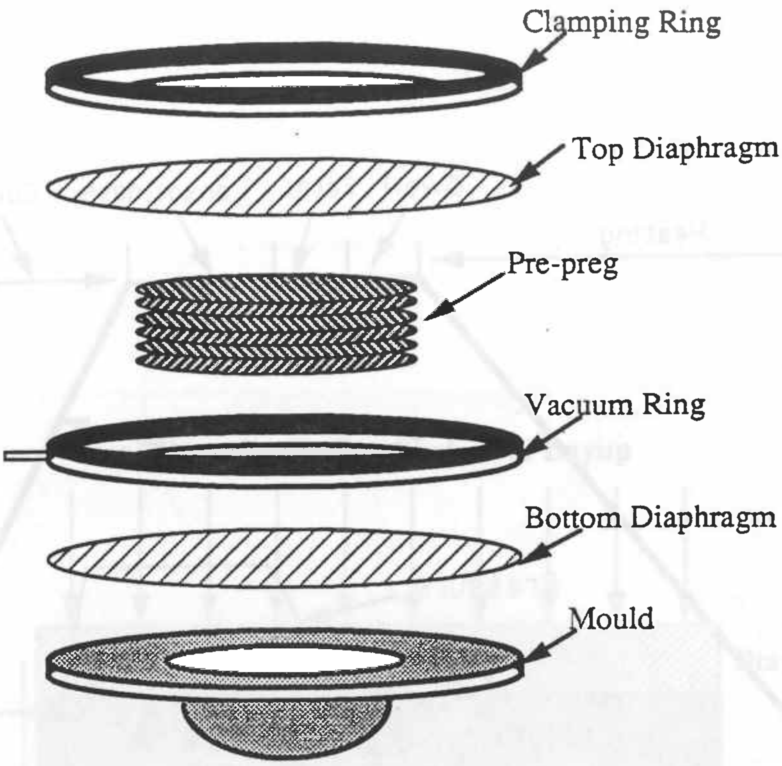

Fig. 2(a) Exploded view of a typical mould and layup assembly used in the diaphragm forming process. (*courtesy of M. Monaghan* [1])

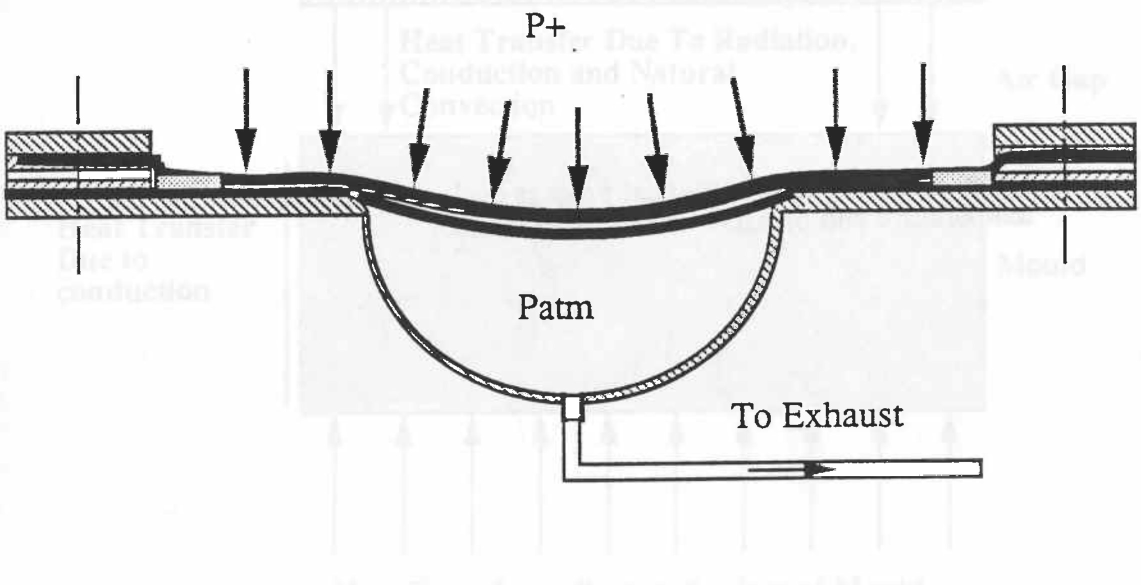

Fig. 2(b) Schematic of forming process showing the layup being forced into the cavity of the mould. (*coutesy of Mr. M. Monaghan* [1])

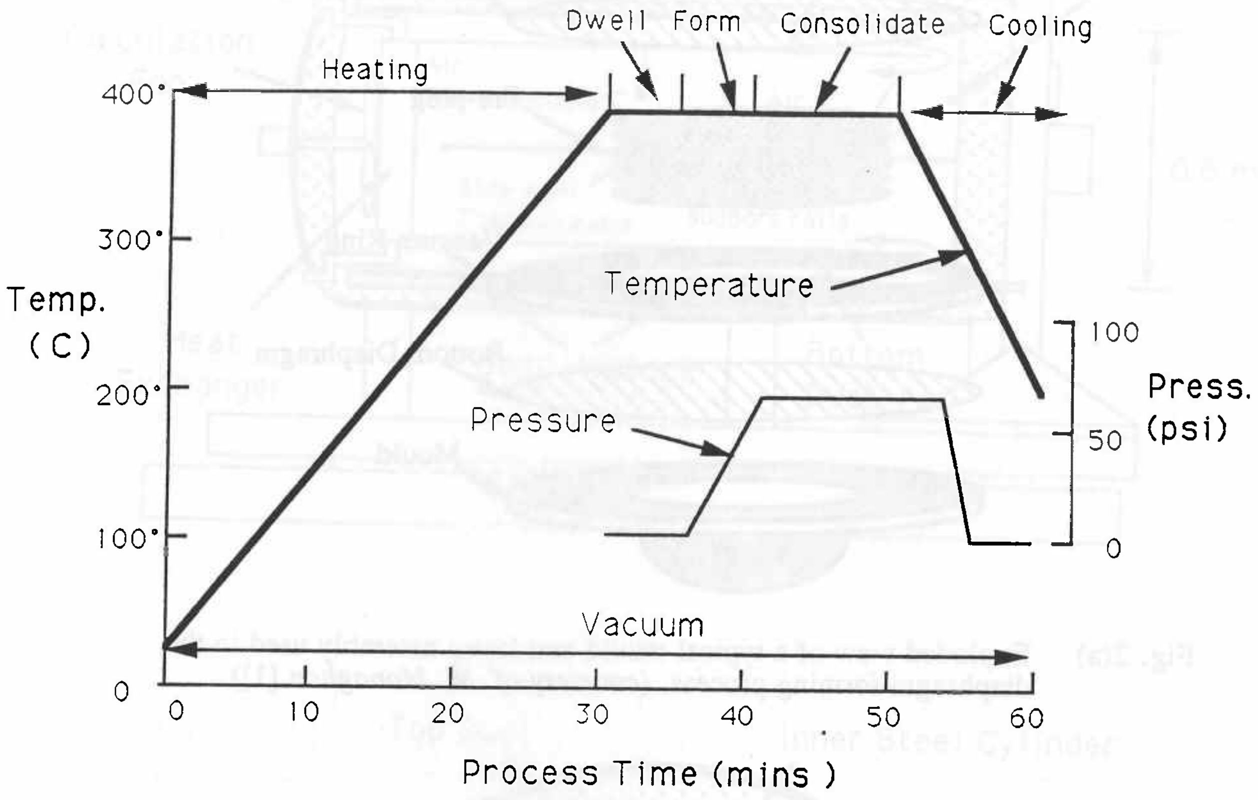

Fig. 3 Schematic diagram of a typical process cycle for APC-2, showing the temperature and pressure curves against time.

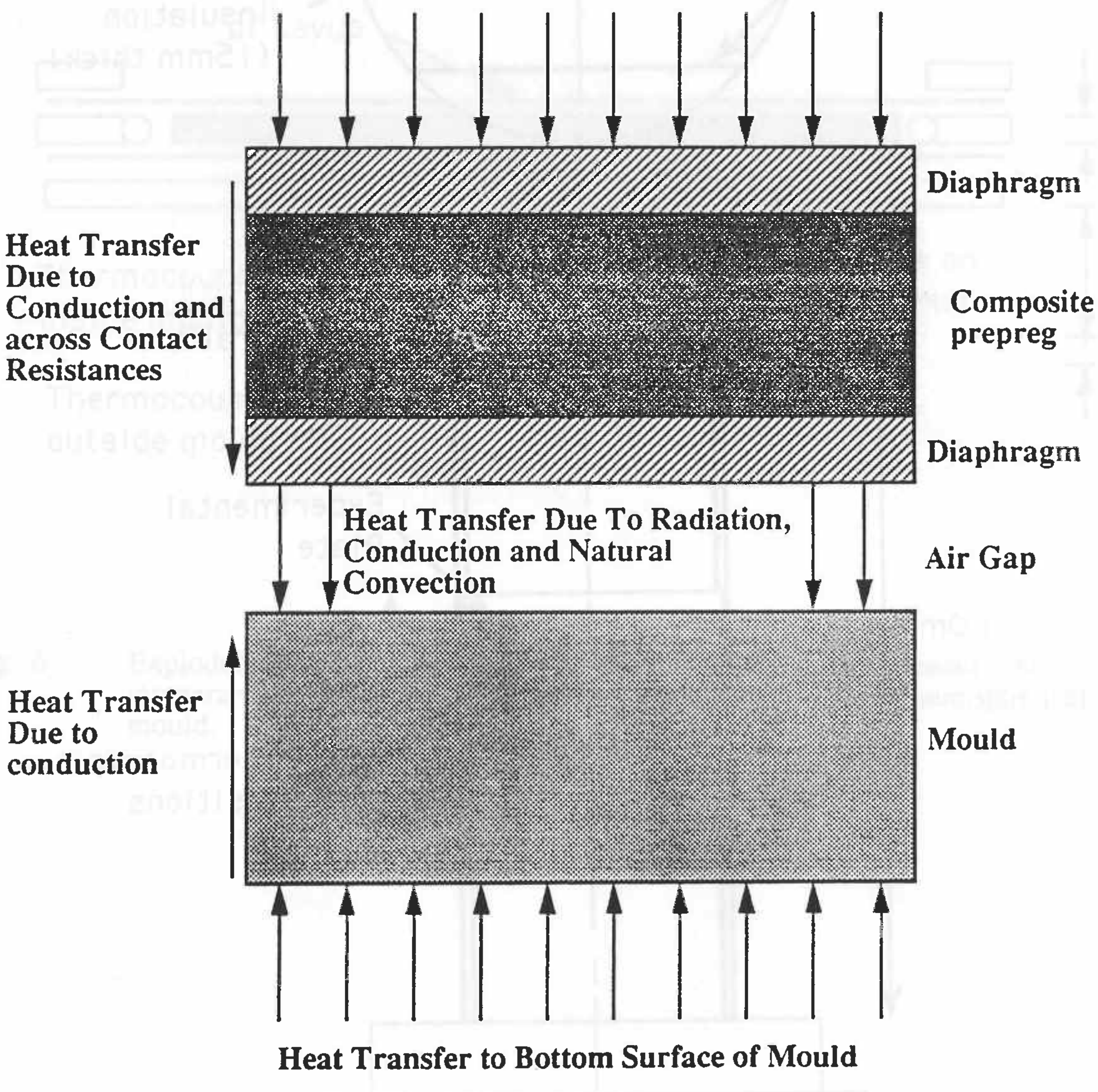

Fig. 4 Schematic diagram of heat transfer mechanisms through a typical mould and layup.

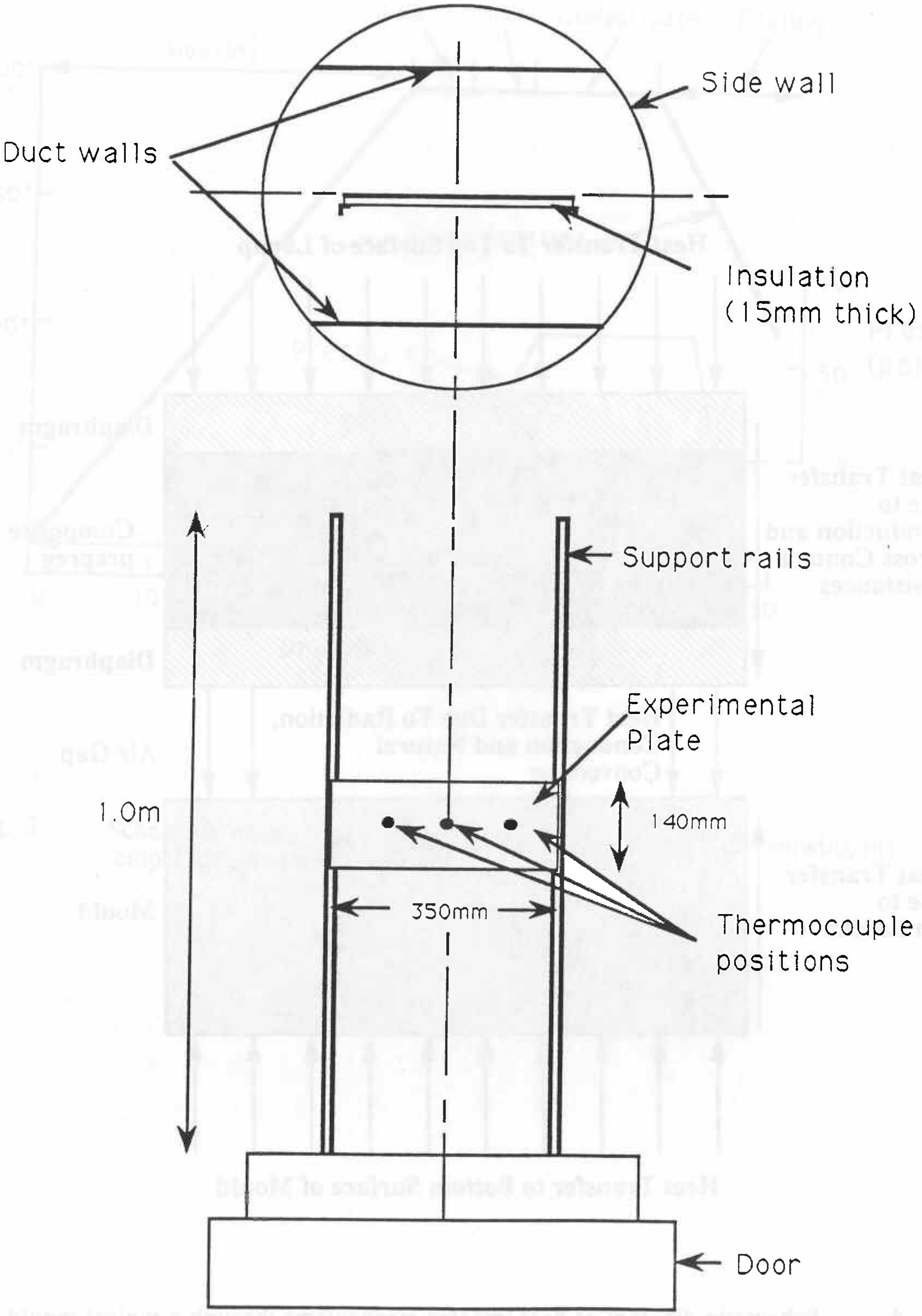

Fig. 5 Scale diagram of size and typical position of experimental plate in relation to the autoclave interior and support rails.

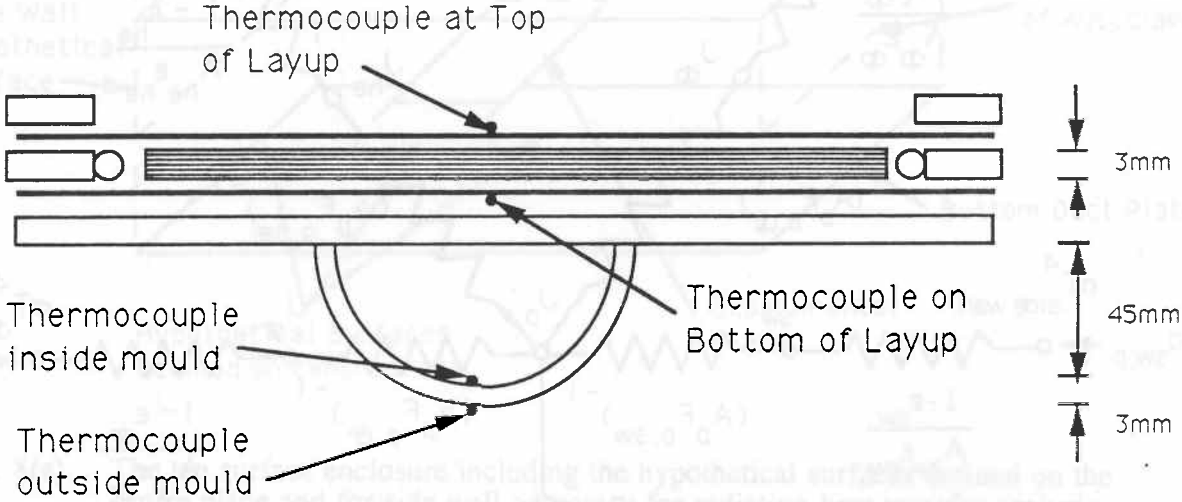

Fig. 6 Exploded view showing position of thermocouples used to measure the temperature distribution through the mould and layup in the hemispherical mould.

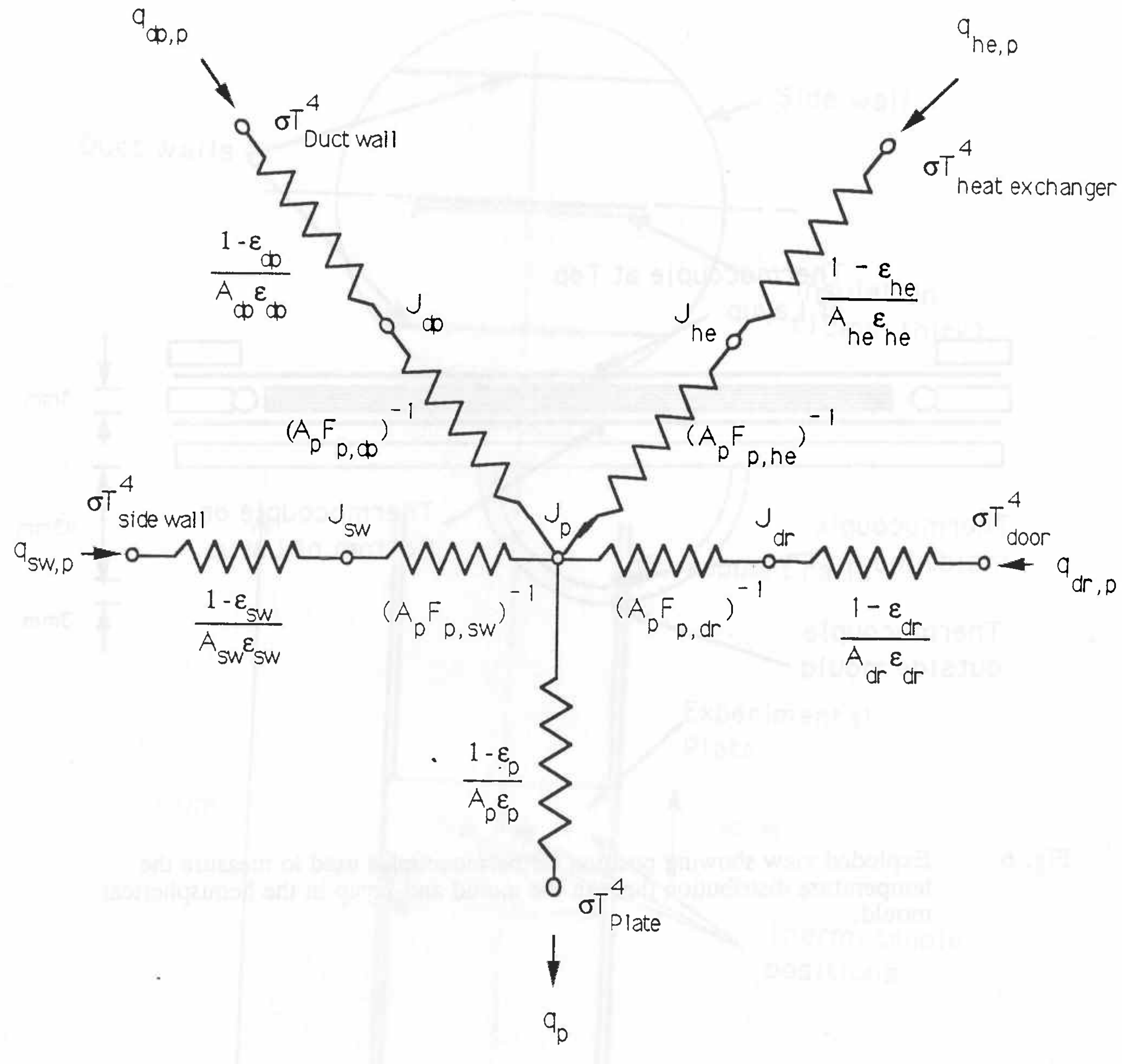

Fig. 7 Network representation of the radiation heat transfer between the different interior surfaces of the autoclave.

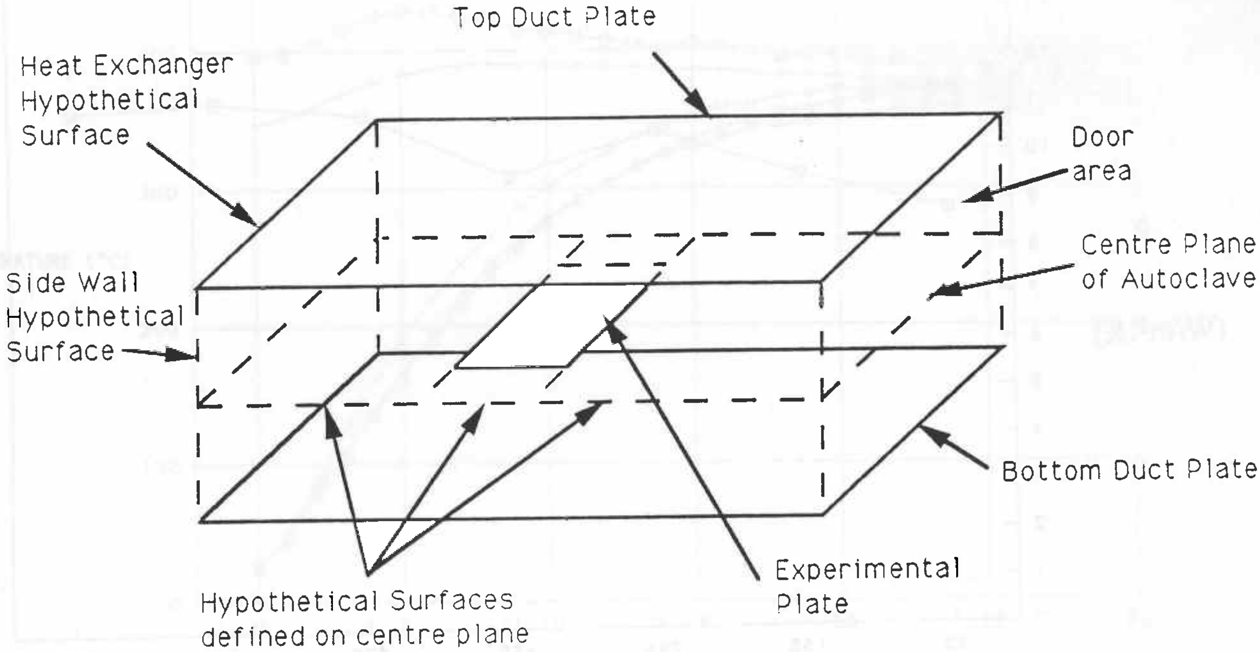

Fig. 8(a) The ten surface enclosure including the hypothetical surfaces defined on the centre plane and for side wall necessary for radiation heat transfer analysis within the top half of the autoclave.

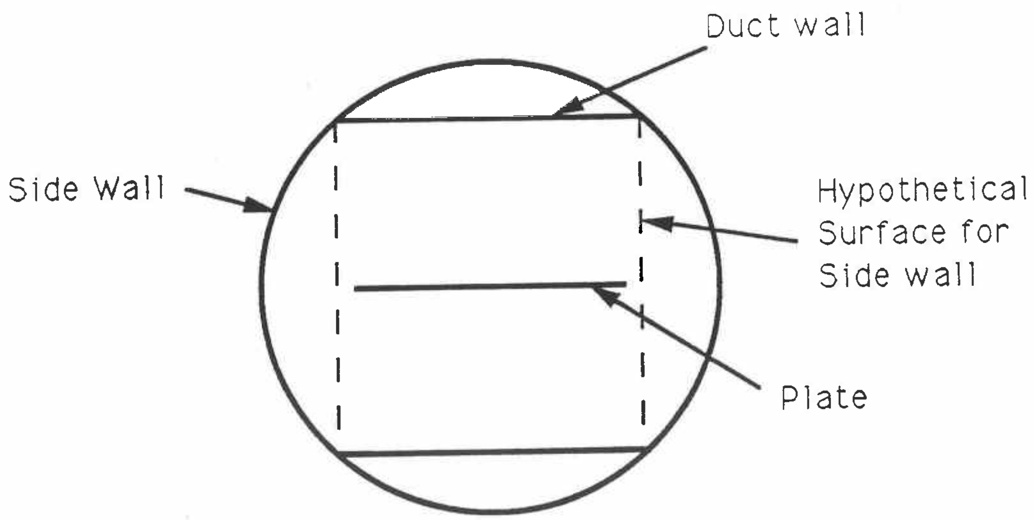

Fig. 8(b) Front view of autoclave showing hypothetical surface for side wall in autoclave radiation analysis.

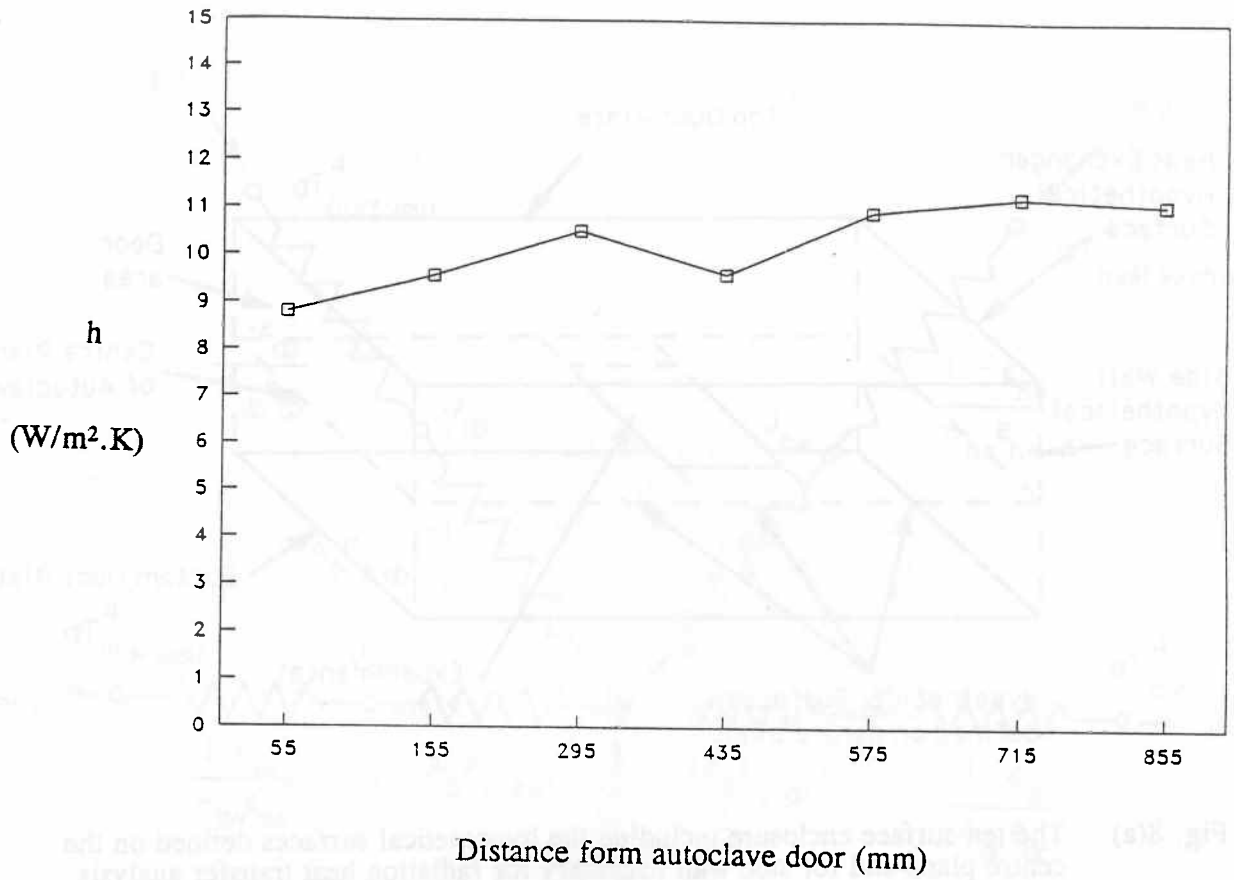

Fig. 9 Variation of the average convection coefficient over a flat plate with position on the support rails within the UCG experimental autoclave.

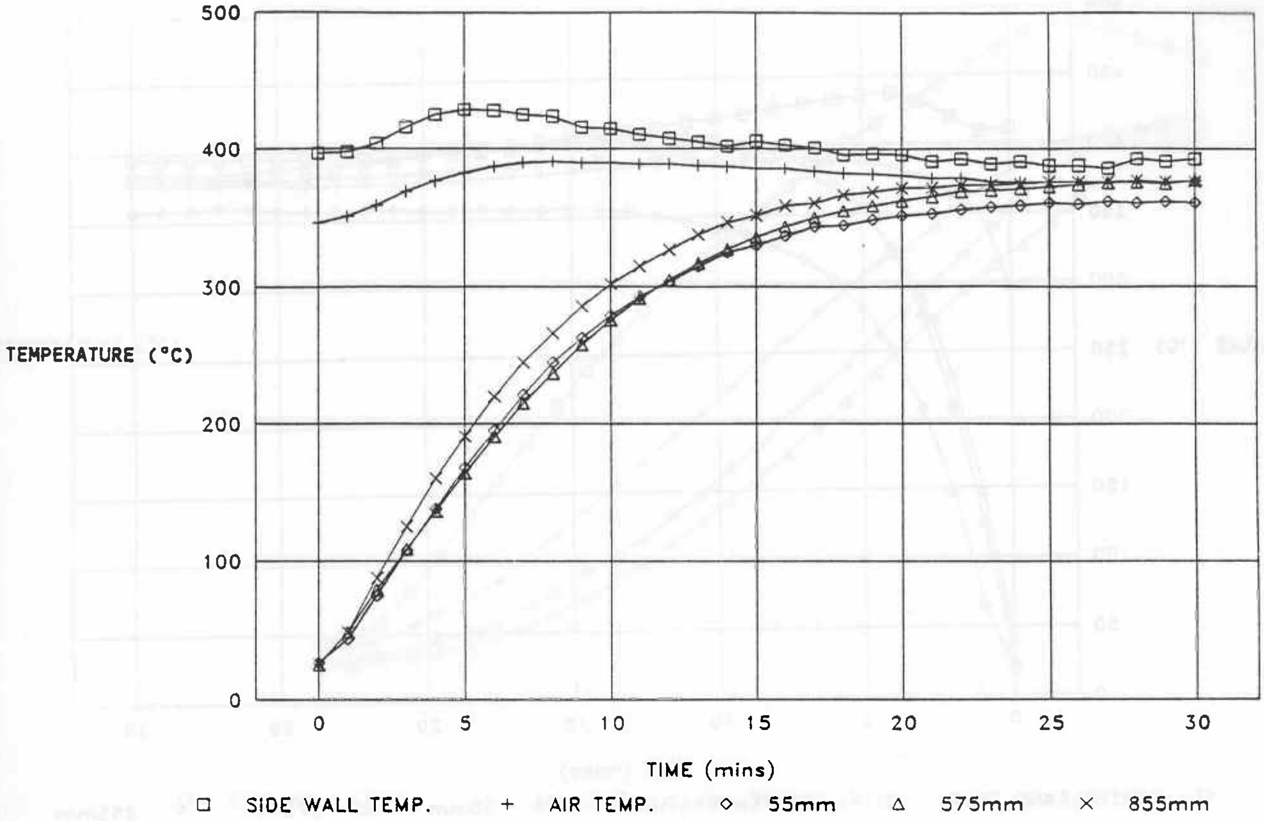

Fig. 10 Plot of temperature against time for low emmissivity plate, heated in preheated UCG autoclave, for three different distances from the door.

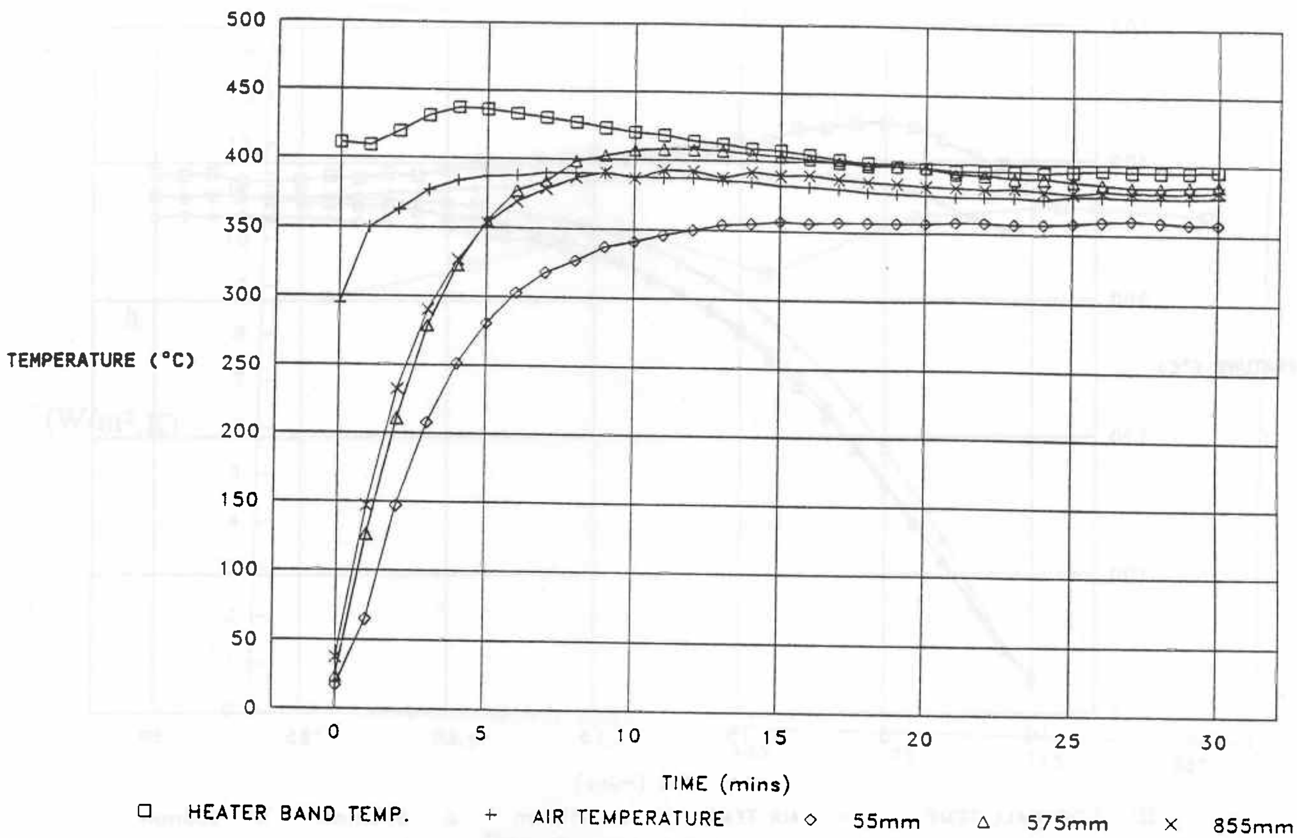

Fig. 11 Plot of temperature against time for high emmissivity plate (e=0.95), heated in preheated UCG autoclave, for three different distances from the door.

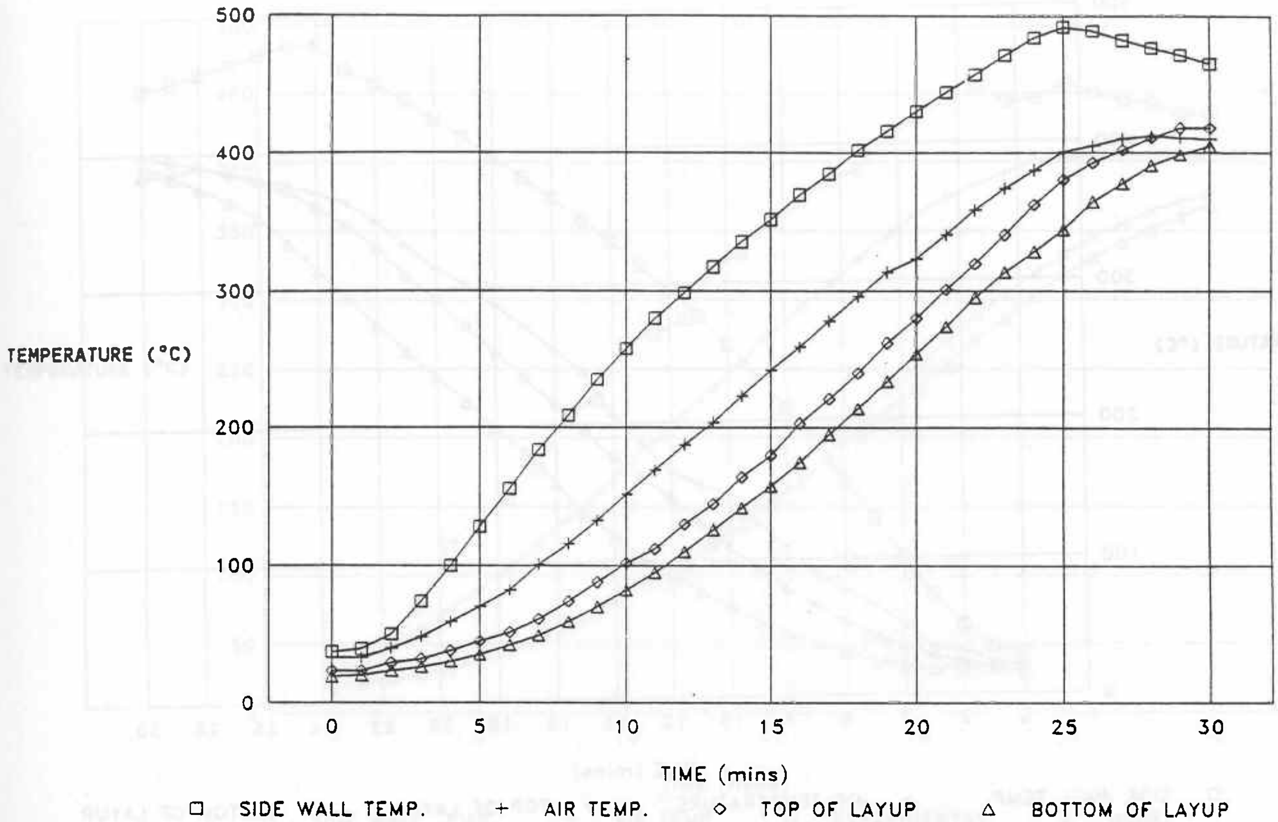

Fig. 12 Plot of temperature distribution through hemispherical mould and consolidated layup, heated within a non-preheated autoclave.

Note:- The outside and inside mould temperatures show little variation from the temperatures at the top of layup and bottom of layup respectively and are not plotted for clarity.

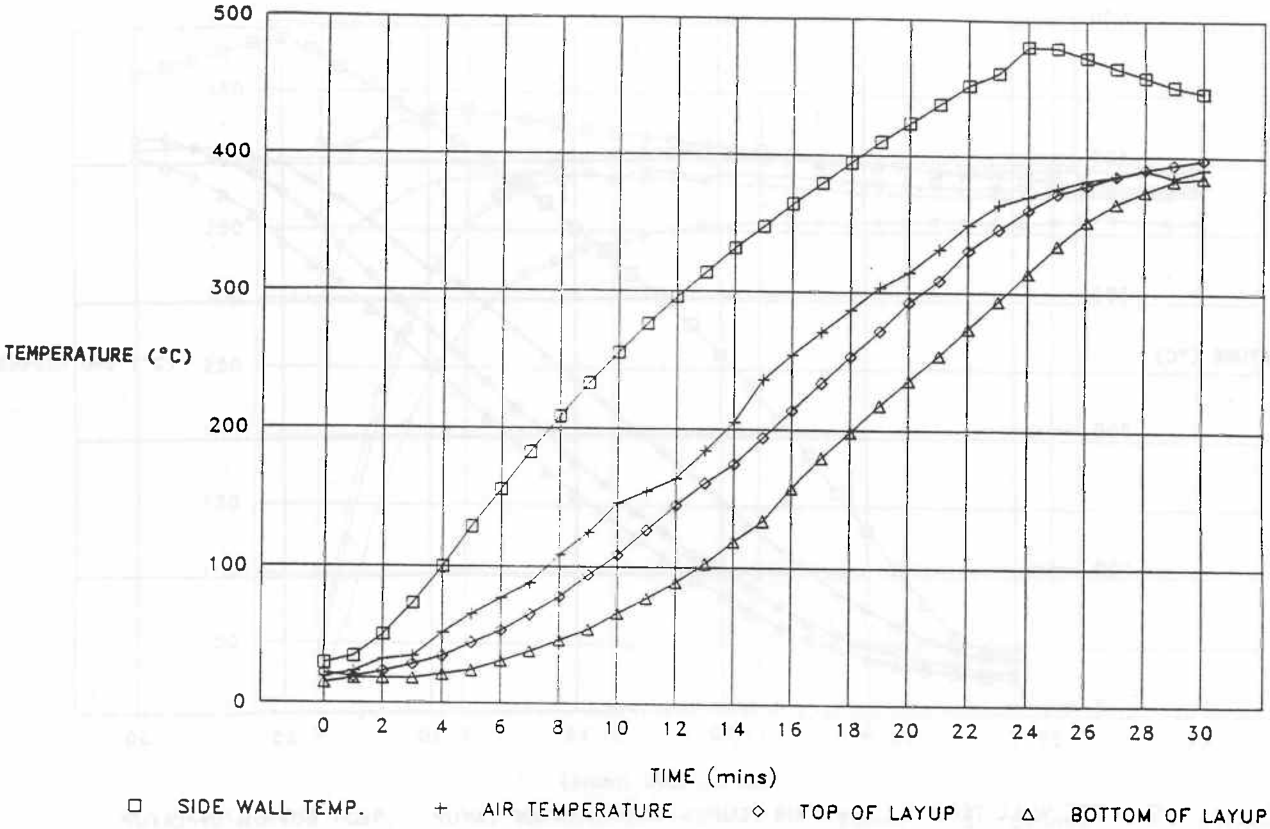

Fig. 13 Plot of temperature distribution through hemispherical mould and unconsolidated layup, heated within a non-preheated autoclave.

Note:- The outside and inside mould temperatures show little variation from the temperatures at the top of layup and bottom of layup respectively and are not plotted for clarity.

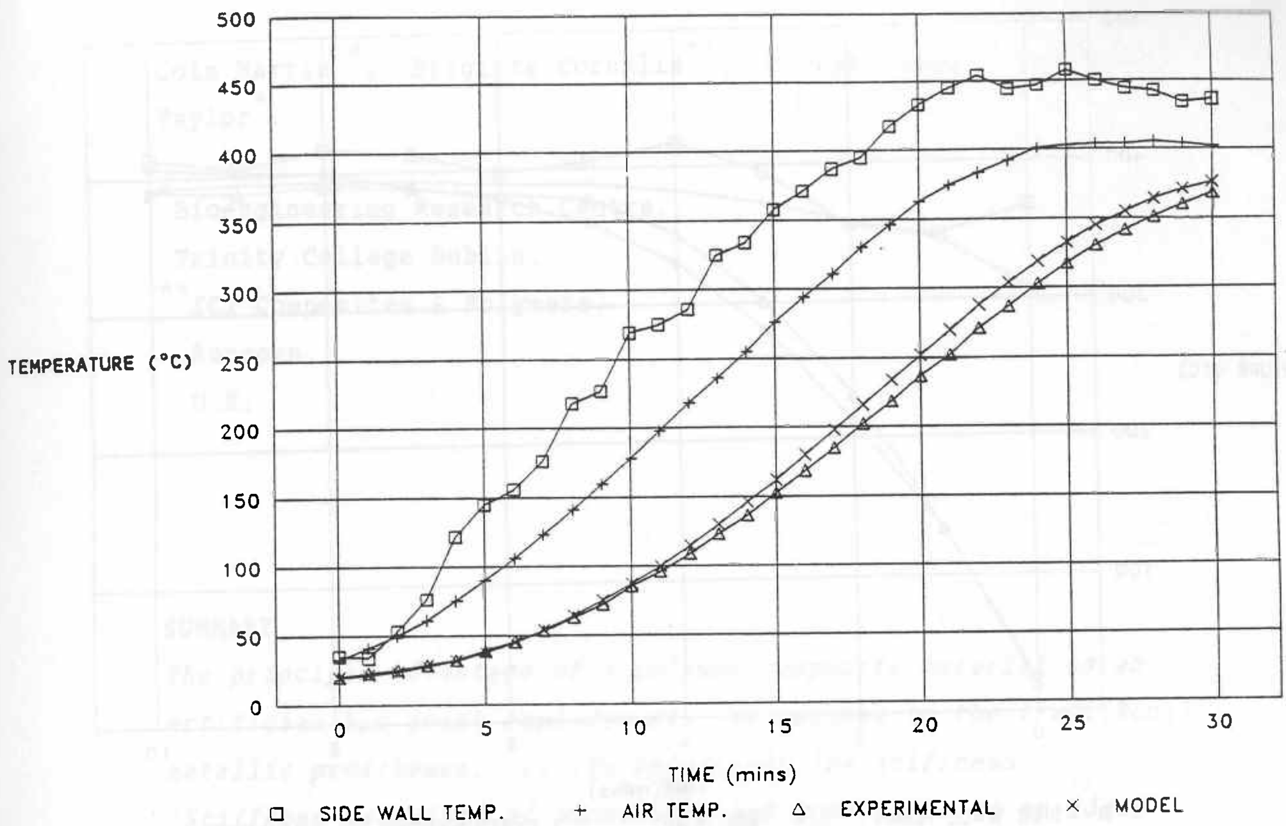

Fig. 14 Comparison of model and experimental results for the polished brass plate, at 575mm form door, heated in a non-preheated autoclave. The emmissivity of the plate is assumed to be 0.05.

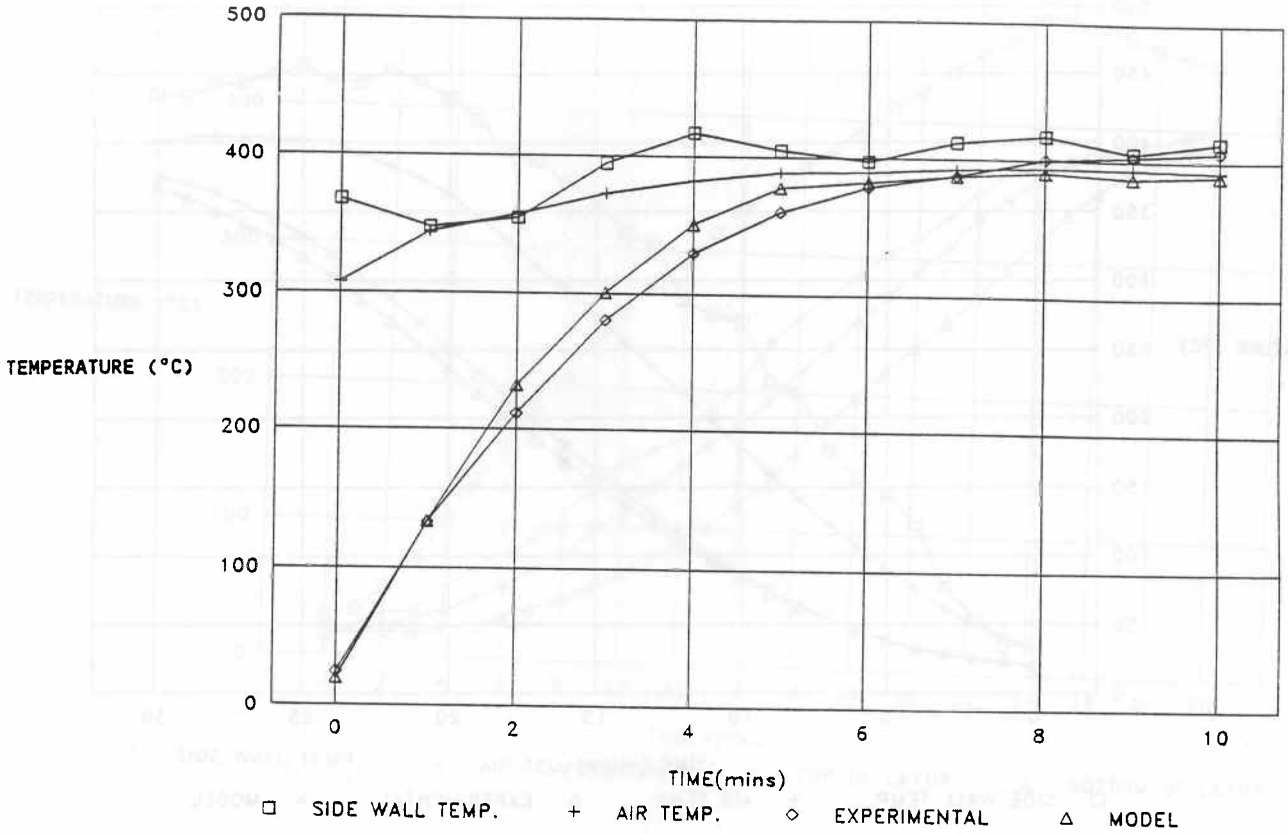

Fig. 15 Comparison of model and experimental results for high emmissivity plate (e=0.95) at 575mm from door, heated in a preheated UCG autoclave.