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Thermal decomposition of a wood particle. Temperature profiles on the solid surface

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Abstract

The calculation of the weight loss during the thermal decomposition of lignocellulosic materials involves the solution of the heat and mass balance equations. In order to solve these equations it is necessary to know the temperature on the solid surface, which can vary at different points and can also be very different from the gas temperature. In this work, an experimental study was carried out in a system which allows the use of large particle sizes and the simulation of different operating conditions. In this study, the temperatures on the solid surface were measured and compared with those corresponding to the empty reactor.

INTRODUCTION

The knowledge of the weight loss during the thermal decomposition of lignocellulosic materials is very important for the design and optimization of different reactors (moving bed, rotatory furnace...) used in gasification and pyrolysis processes in which relatively large particle sizes are involved.

As the solid particle size increases, the inner temperature profiles become steeper [1–3], which exerts a great influence on the solid conversion [1] and on the product distribution obtained [2]. The calculation of the temperature at several points inside the solid involves the solution of the heat and mass balance equations. These equations include the kinetic equation, the heat generated or consumed during the process and the heat transfer phenomena [1,2,4–6]. In order to solve these equations it is necessary to know the temperature on the solid surface, which can vary at different points and can also be very different from the gas temperature [7].

In this work, therefore, an experimental study has been carried out in which the temperatures on the solid surface were measured and compared with those corresponding to the empty reactor.

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Initially, with the aim of minimizing the temperature profiles inside the reactor, a study of the influence of the operating conditions on the temperature at several points of the reactor was performed. This would allow us to achieve the most homogeneous thermal environment around the particle and it would facilitate the mathematical resolution of the equations.

EXPERIMENTAL METHOD

The experimental system consists of a cylindrical reactor discontinuous for the solid, an electrical furnace connected to a temperature and heating control system, and a data logger which allows us to join up ten thermocouples. This experimental device allows the measurement of the weight loss of the solid during its thermal decomposition through a precision balance connected to the sample inside the reactor. A scheme of the reactor is shown in Fig. 1.

Experiments from 30 up to 650°C with a heating rate of the system of 12°C min^{-1} have been performed. Once 650°C is reached, the system remains at this temperature for 12 minutes. Nitrogen was used as an inert gas. The connection between the balance and the sample is placed exactly at the central point of the reactor head. Because of this, the inlet of the inert gas is situated approximately at $r = 3.25$ cm from the central point.

In order to minimize the temperature profiles inside the reactor, the influence of the nitrogen flow rate on these profiles has been studied. For flow rates between 15 and 50 N $\text{cm}^3\ \text{s}^{-1}$, thermocouples were placed at several points of the reactor to know the temperature at different depths ($z = 4$, 6, 8, 10, 12, 15 and 18 cm), radii ($r = 0$, 1, 2, 3 and 4 cm) and angles ($\theta = 0$, 90, 180 and 270°); θ is the angular cylindrical coordinate. The location of the nitrogen inlet corresponds to $\theta = 90°$, and from here the remaining positions are established in an anticlockwise direction, Fig. 1.

With the aim of determining the boundary conditions in relation to the mathematical resolution of the model, experiments with wood spheres ($D = 2$, 4 and 5.65 cm) were carried out in which the temperature at different points of the solid surface was measured. These points correspond to different α values, α being the angle which sweeps the plane of the inert gas flow direction, $\alpha = 0°$ corresponding to the direction of the radius vector opposite to the flow direction and $\alpha = 180°$ to the flow direction.

TEMPERATURE PROFILES INSIDE THE REACTOR. RESULTS AND DISCUSSION

The experiments carried out with the empty reactor (without sample) have shown the existence of longitudinal, radial and angular temperature

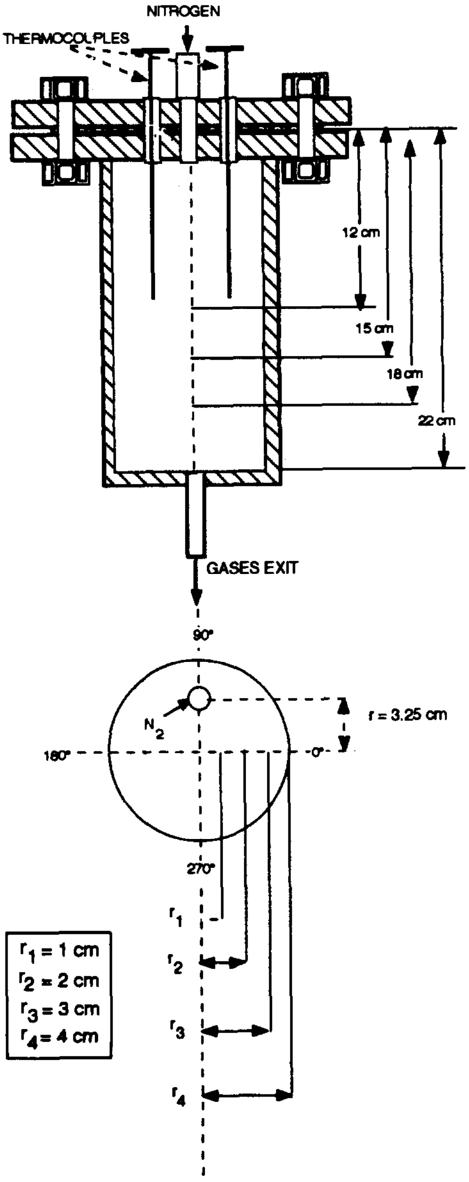

Fig. 1. Scheme of the reactor.

profiles inside the reactor. In addition, a variation of the nitrogen flow may appreciably modify these profiles.

In general, for any radius, angle and nitrogen flow, the gas temperature logically increases as the depth does. Now, it is also observed that from $z = 12$ cm the longitudinal profiles are negligible. An example is shown in Fig. 2. This fact is very interesting for selecting the depth in which the sample in the reactor must be placed, which would be $z \geq 12$ cm.

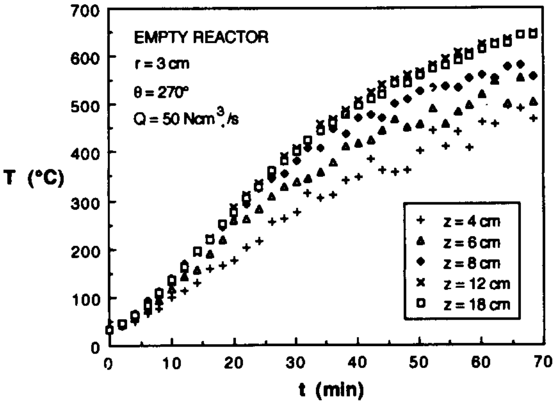

Fig. 2. Longitudinal temperature profiles inside the empty reactor.

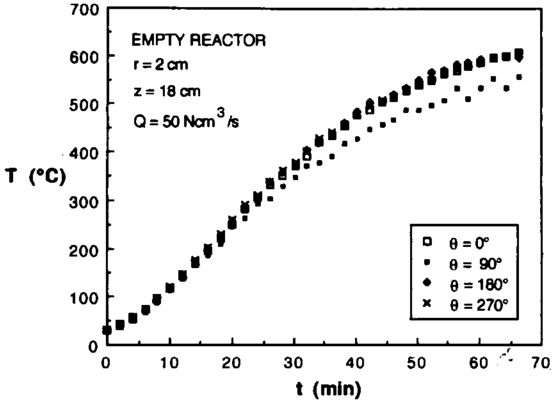

Fig. 3. Angular temperature profiles using a high nitrogen flow rate.

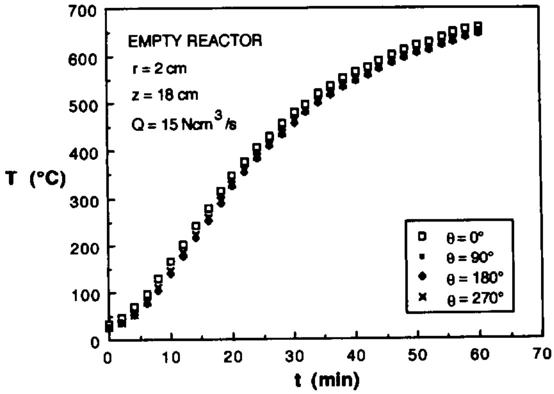

Fig. 4. Angular temperature profiles using a low nitrogen flow rate.

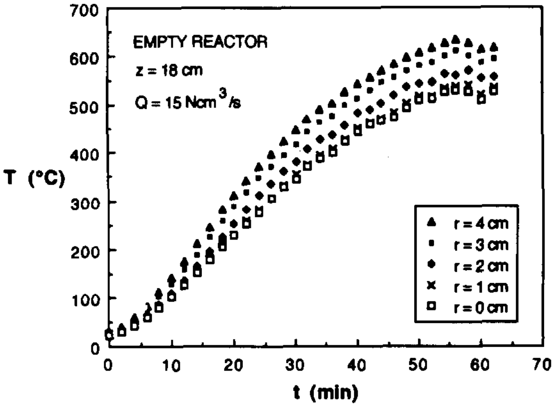

Fig. 5. Radial temperature profiles inside the empty reactor.

The appearance of the angular profiles could be due to the fact that the nitrogen entry is located at $z = 0$, $r = 3.25$ cm and $\theta = 90°$. When the flow rates are high (e.g. 50 N cm^3 s^{-1}) it is observed that, for each radial position and depth, the temperatures obtained for $\theta = 90°$ are lower than those corresponding to other θ values. These differences are higher between $r = 2$ and 3 cm, and they decrease as z increases. However, when a 50 N cm^3 s^{-1} flow rate is used, these angular profiles are marked even for high values of z; Fig. 3. This effect, the difference of the temperature between $\theta = 90°$ and other θ values, decreases considerably when a lower nitrogen flow is used, as can be observed in Fig. 4 for 15 N cm^3 s^{-1}.

Regarding the radial profiles, the temperature shows an increase as the radius does. This is logical, since the heating flow is lateral. Besides, it is observed that profiles appear for any value of z, θ, and nitrogen flow. An example is shown in Fig. 5 for low nitrogen flow and high depths.

From this study, a 15 N cm^3 s^{-1} nitrogen flow rate and a depth between 12 and 18 cm for the location of the sample have been selected for this reactor. In this way it is possible to minimize the temperature profiles, with only the radial profiles remaining.

TEMPERATURES ON THE SOLID SURFACE. RESULTS AND DISCUSSION

The temperature on the solid surface is not only determined by the temperature in the empty reactor. The heat generated or consumed during the thermal decomposition of the material itself will influence the temperature too, and it is also necessary to consider that the particle location decreases the free surface of the gas path and modifies its flow.

For determining these temperatures, a series of experiments with a nitrogen flow of 15 N cm^3 s^{-1} and using wood spheres of different sizes ($D = 2$, 4 and 5.65 cm) has been carried out. In these experiments thermo-

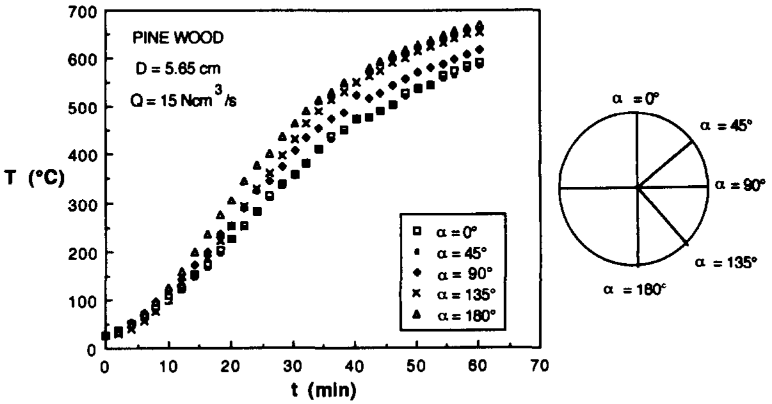

Fig. 6. Temperature at different points on the solid surface.

couples were placed at different points on the particle surface. For each sphere size, results are obtained for the same particle radius which correspond to different radii and depths in the reactor. For each experiment, these two variables can be lumped together in α. Obviously, for different solid sizes, the same α value can correspond to different depths and radii of the reactor.

The temperatures obtained versus time for several α values are shown in Figs. 6, 7 and 8. It can be observed that similar trends are obtained, the temperature on the solid surface increasing as the α value does.

The temperature at the different points has been analysed and compared with the temperature at the equivalent point in the empty reactor. For this, the points of each experiment which correspond to the same reactor radius have been grouped together.

The results corresponding to $r = 0$ ($\alpha = 0°$ and 180°) are shown in Figs. 9, 10 and 11. It can be observed that the trends are very similar. At low

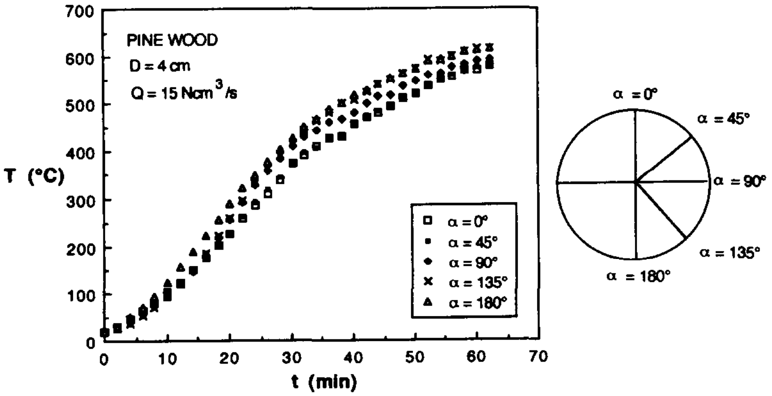

Fig. 7. Temperature at different points on the solid surface.

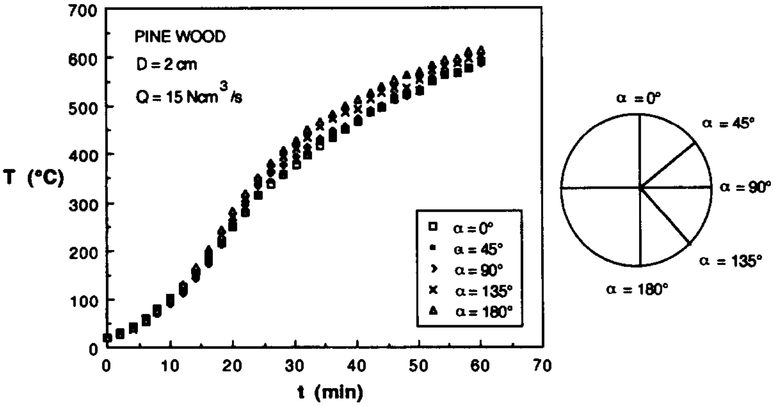

Fig. 8. Temperature at different points on the solid surface.

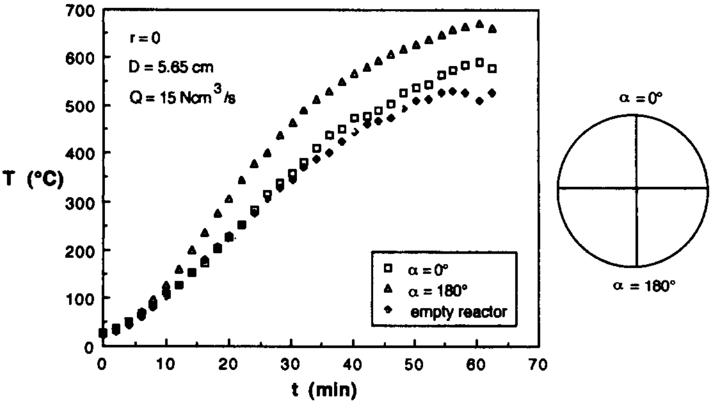

Fig. 9. Comparison between temperatures at $r = 0$.

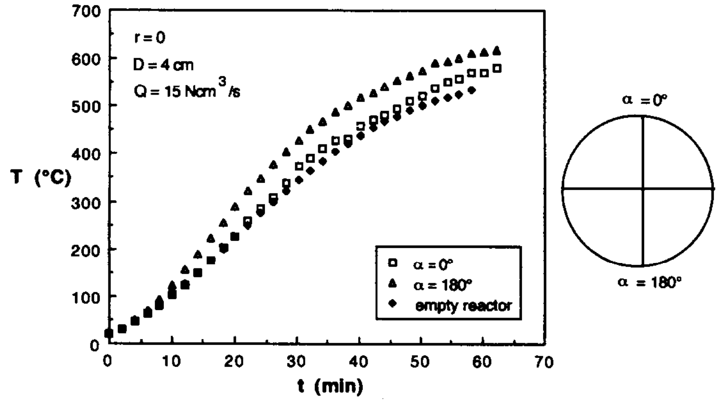

Fig. 10. Comparison between temperatures at $r = 0$.

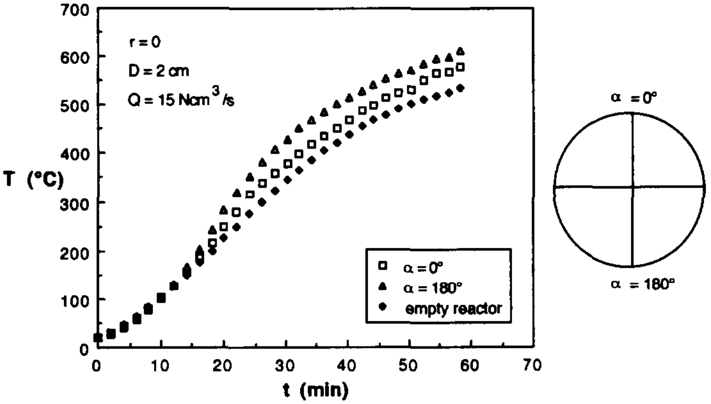

Fig. 11. Comparison between temperatures at $r = 0$.

temperatures, before the decomposition of material begins, the temperatures at these points are practically equal to each other and to that of the corresponding point in the empty reactor.

At higher temperatures, the points on the solid surface acquire a greater temperature than that of the equivalent point in the empty reactor, the gradient being much steeper for $\alpha = 180°$. These differences are explained because the thermal decomposition of the material is essentially exothermic, and therefore the gases originating in the solid are hotter. Besides, these gases would flow chiefly downwards with the gas direction, which explains why the temperature for $\alpha = 180°$ is higher than for $\alpha = 0°$. This greater temperature at $\alpha = 180°$ can also be marked: the gas gets hotter because previously it was forced to flow near the reactor wall, where the temperature is higher.

This fact can be corroborated if the temperature at $\alpha = 180°$ for different sizes is compared. In Fig. 12 those corresponding to 2 and 5.65 cm are

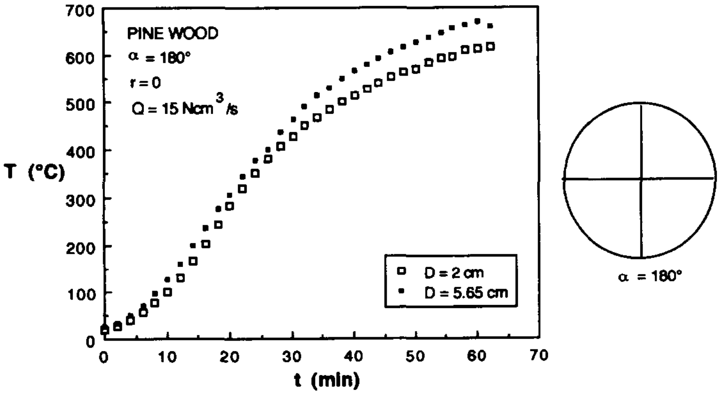

Fig. 12. Comparison between temperatures at $\alpha = 180°$ for different particle sizes.

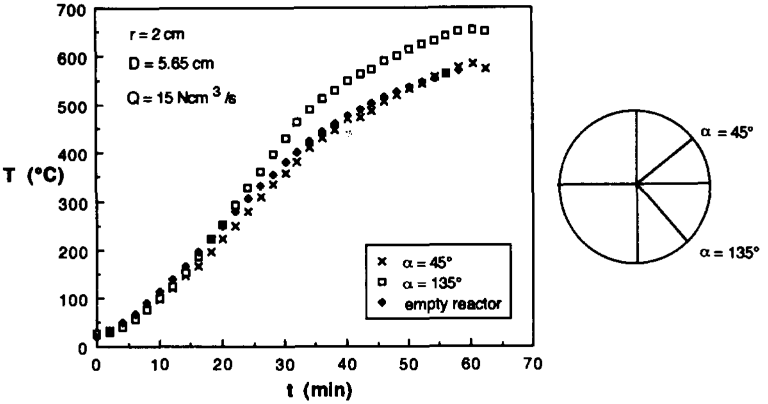

Fig. 13. Comparison between temperatures on the solid surface and in the empty reactor.

shown. For small particle sizes, the deviation that the gas undergoes due to the presence of the sphere is not so high as for $D = 5.65$ cm. Because of this, the flow does not get so close to the reactor walls and it does not get so hot. In addition, it is necessary to take into account the greater amount of gases produced in the large particles. For other α values, the results are not comparable for different particle sizes, since these α values correspond to different reactor radii.

Figures 13, 14 and 15 show the results for $\alpha = 45°$ and 135°. It must be taken into account that for particle sizes of $D = 5.65$, 4 and 2 cm these points correspond to a reactor radius of 2, 1.4 and 0.7 cm respectively.

At low temperatures, in which the thermal decomposition has not yet started, it is observed that for higher particle sizes, the corresponding point in the empty reactor shows a slightly higher temperature than when the wood particle is present. This can be explained because, when there is a sample, the gas that flows over this point is also made up of the gas that

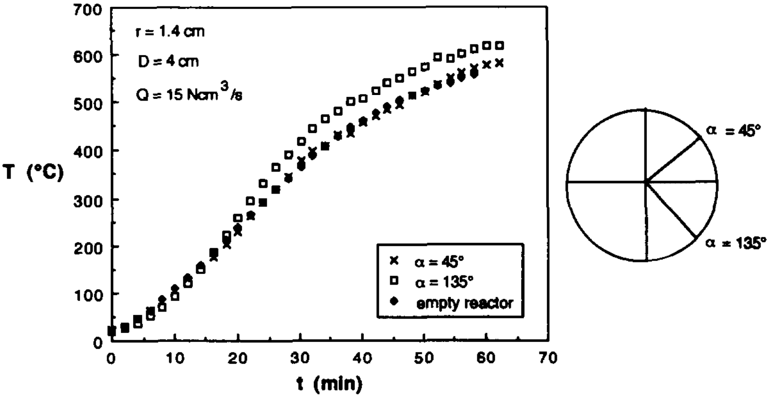

Fig. 14. Comparison between temperatures on the solid surface and in the empty reactor.

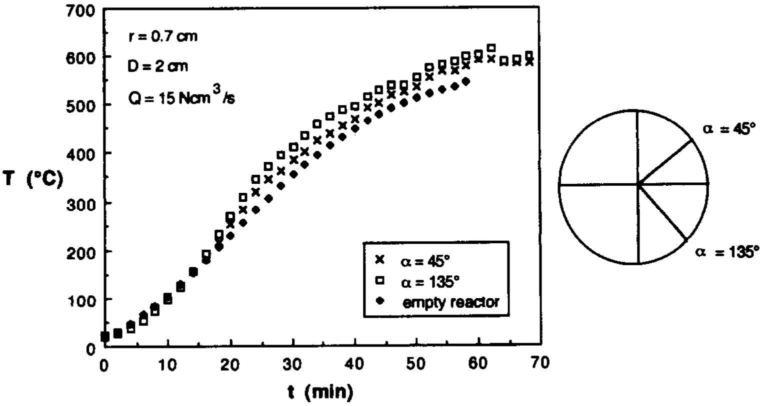

Fig. 15. Comparison between temperatures on the solid surface and in the empty reactor.

flows over the points corresponding to smaller reactor radii, which have a lower temperature.

When the reaction starts, depending on the particle size, some differences can be appreciated when the temperatures at the point $\alpha = 45°$ are compared with the equivalent point in the empty reactor. For $D = 5.65$ cm, the temperature in the empty reactor is slightly higher than at $\alpha = 45°$. The trend changes as the solid size decreases. These differences can be explained taking into account that results for different reactor radii are compared. When this radius increases, the temperatures in the empty reactor are higher, and furthermore, when the solid has been put into position, the gas at $\alpha = 45°$ originates from mixtures with lower temperatures, since they proceed from smaller reactor radii.

Figures 16, 17 and 18 show the comparison between the temperature at the point $\alpha = 90°$ on the solid surface and that at the point in the empty

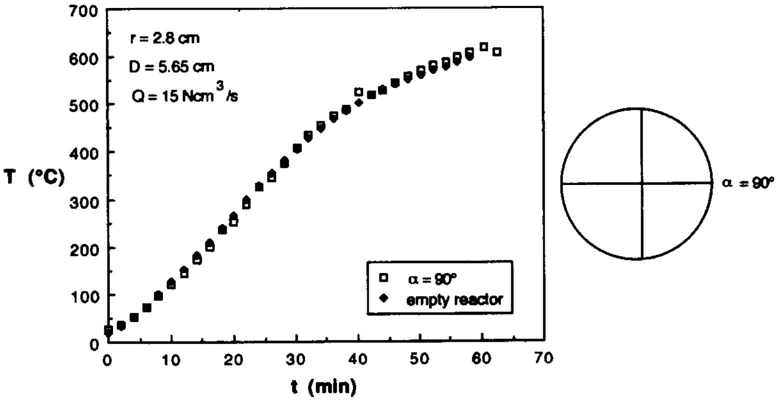

Fig. 16 Comparison between temperatures on the solid surface and in the empty reactor.

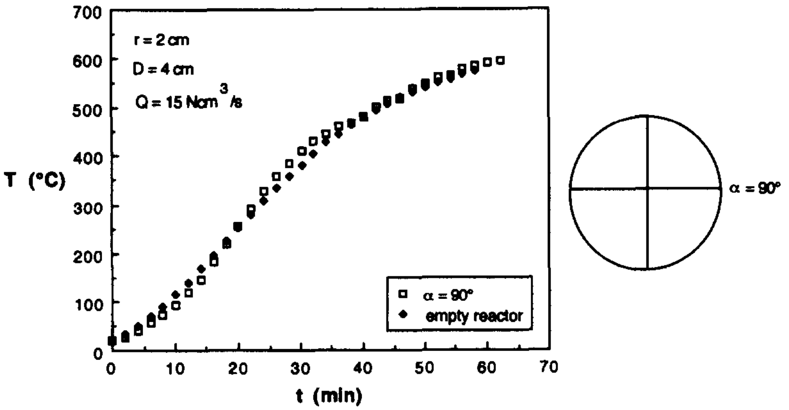

Fig. 17. Comparison between temperatures on the solid surface and in the empty reactor.

reactor corresponding to the same radius, the radius being $r = 2.8$, 2 and 1 cm for the sizes $D = 5.65$, 4 and 2 cm respectively.

Before the onset of the reaction, the point in the empty reactor is slightly hotter than that of the wood owing to the presence of the particle itself. Once the pyrolysis starts, some differences are observed. For $D = 4$ and 2 cm, Figs. 17 and 18, the influence of the hot gases produced is clear, since the temperature at $\alpha = 90°$ on the solid surface is higher than that of the point in the empty reactor. However, if Fig. 16 is observed, it can be seen that in the case of a large particle size, $D = 5.65$ cm, both the point in the empty reactor and that on the solid surface have practically the same temperature during the whole time. In this case, the heat generated in the reaction is compensated for by the colder gases that proceed from above the particle and are caused to deviate by its presence.

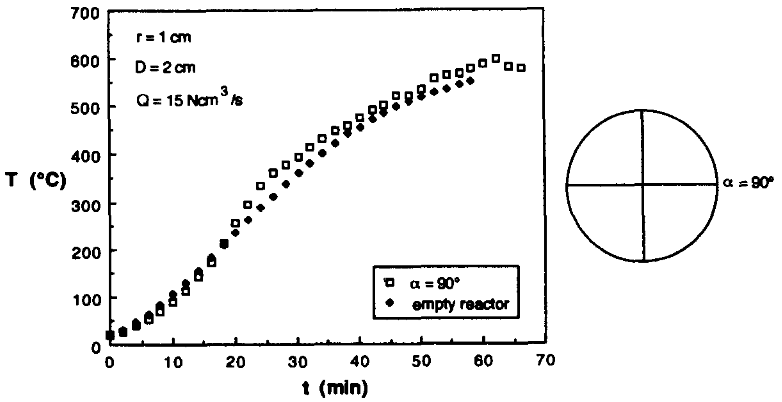

Fig. 18. Comparison between temperatures on the solid surface and in the empty reactor.

CONCLUSIONS

(i) There are radial, angular and longitudinal temperature profiles inside the empty reactor. The longitudinal and angular profiles can be eliminated by using a low gas flow rate, 15 N cm^3 s^{-1}, and placing the sample between $z = 12$ and 18 cm.

(ii) Temperature differences also appear among the different points on the solid surface, corresponding to different α values. The general trend is that the temperature increases as α does.

(iii) The hot gases produced during the thermal decomposition of the lignocellulosic material affect the different temperatures on the solid surface.

(iv) The deviation of the gas flow direction produced by the presence of the particle itself affects the temperature differences on the solid surface also.

NOTATION

D	particle diameter
Q	nitrogen flow rate
r	reactor radius
t	time
T	temperature
z	reactor depth
α	angle which sweeps the plane of the inert gas flow direction
θ	angular cylindrical coordinate

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