Heating characteristics of a new type of Hartmann–Sprenger tube

E. Brocher and J.-P. Ardissone*

The heating characteristics of various Hartmann–Sprenger tubes are studied with the view to using the device as a fluidic igniter. To improve the performance of the classical Hartmann generator, a so-called 'needle' generator is used. The influences of various parameters are considered: the pressure and nature of the driving jet, cavity shape and physical properties of the tube material. Temperatures at the end walls of the tubes have been measured with thin (25 μm diameter) thermocouples. With a stepped cavity, a temperature of 300 °C was recorded after 49 ms with nitrogen, after 6.9 ms with argon and after 1.7 ms with helium. A maximum temperature of 500 °C was obtained with nitrogen, 800 °C with argon and 1100 °C with helium.

Key words: *ignition, Hartmann–Sprenger tube, needle generator*

The Hartmann–Sprenger tube (HS tube) is a device in which a high-speed jet is directed towards the entrance of a tube which is closed at the other end. Under certain conditions, this driving jet produces a pulsating flow within the tube[1,2]. Its principle of operation is different from that of the so-called 'resonance tube' in which the flow oscillations are driven by a piston[3]. For this latter device, resonance effects occur when the frequency of the piston approaches the eigenfrequency of the tube. For the HS tube, the driving jet flows continuously out of the nozzle and its operating mechanism is attributed to the instability of the shock cell structure of the jet. A distinction between HS tubes and resonance tubes should therefore be made, although earlier accounts have not done so.

Initially the jet penetrates deeply into the cavity and produces a shock wave which is reflected at the closed end. This reflected shock wave moves upstream until it reaches the open end and pushes the driving jet sideways. This is the start of a second phase in which the tube empties. An expansion wave moves towards the end wall, is reflected there, and moves upstream. When this reflected expansion wave arrives at the cavity mouth, it sucks the driving jet into the tube and a new cycle begins. This process has been described in detail elsewhere[4] and is shown in a simplified time–distance diagram in Fig. 1. Also shown is the contact front separating the gas of the driving jet and the indigenous gas oscillating within the cavity. The penetration length L_p of the driving gas increases with the Mach number of the driving jet. Frictional losses and shock-wave irreversibilities produce a rapid heating of the driven gas oscillating within the tube[5–9]. It can be shown that a heating rate of more than 10^6 K/s is feasible in a short (10 mm) tube driven by a helium jet[9]! These heating characteristics have led several investigators to study the possibility of using the HS tube to ignite a

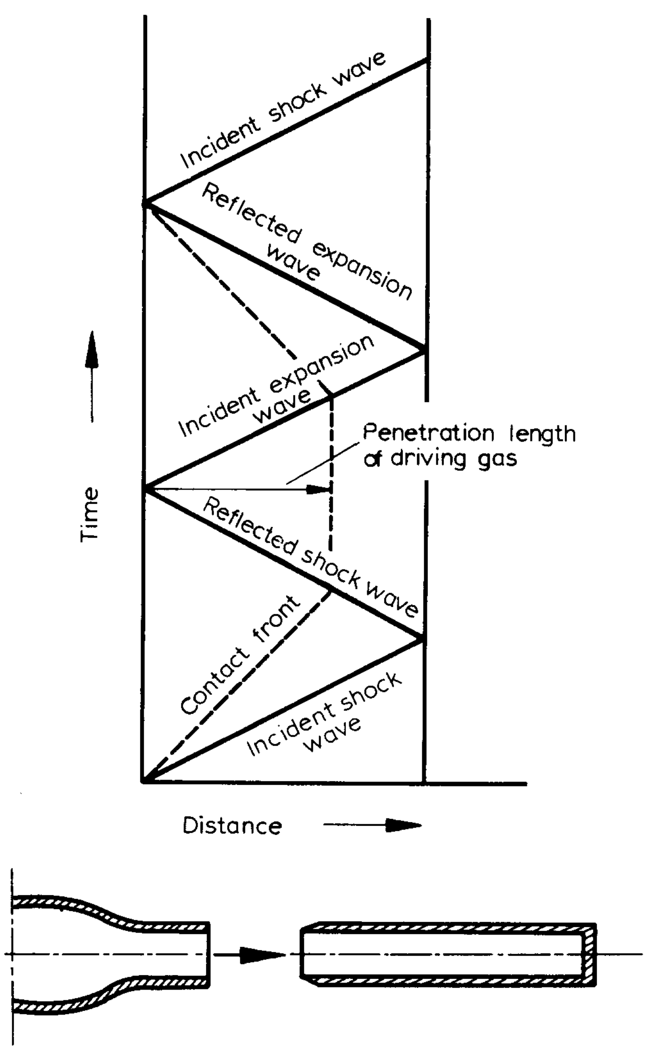

Fig. 1 Simplified wave diagram of HS tube

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pyrotechnic composition[10–12]. The results obtained by these authors are encouraging and warrant further investigation.

The aims of the present work are first, to use the results of the fundamental research carried out on heating effects in HS tubes[8,9] as a guide to the experimental programme; and second, to make use of the so-called 'needle' generator to improve the heating performance of the device. This generator is a modification of the classical HS tube and has more reliable characteristics[13].

In its classical configuration, the HS tube is driven by a sonic jet in which shock cells are present. The operation of the device is very sensitive to the position of the tube mouth within these cells[1,2]. Outside so-called 'instability intervals', no oscillations occur within the tube. Since the cell length depends on the driving pressure of the jet, the device cannot function properly with a falling driving pressure. This is the case for certain applications in which the driven gas is contained in a vessel of limited capacity. For the needle generator, the functioning of the device is not reliant on the shock cell structure. The mode of operation relies on the interaction of waves with the boundary layer developing on the needle. Therefore, for a vessel of limited capacity, the generator will work efficiently over a large pressure range while the container empties.

Experimental set-up

Experiments were conducted with a set-up comprising (Fig. 2):

- bottles of compressed gas (nitrogen, argon, helium)
- a nozzle with a needle laid on its axial centre line
- a fast opening shutter
- HS tubes of various shapes made of various materials
- an optical bench
- thermocouples
- a fast recording system.

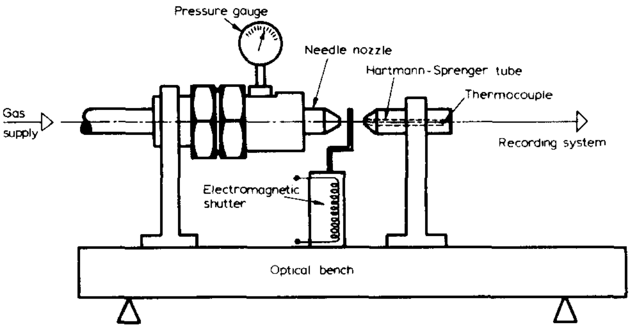

Fig 2 Experimental set-up

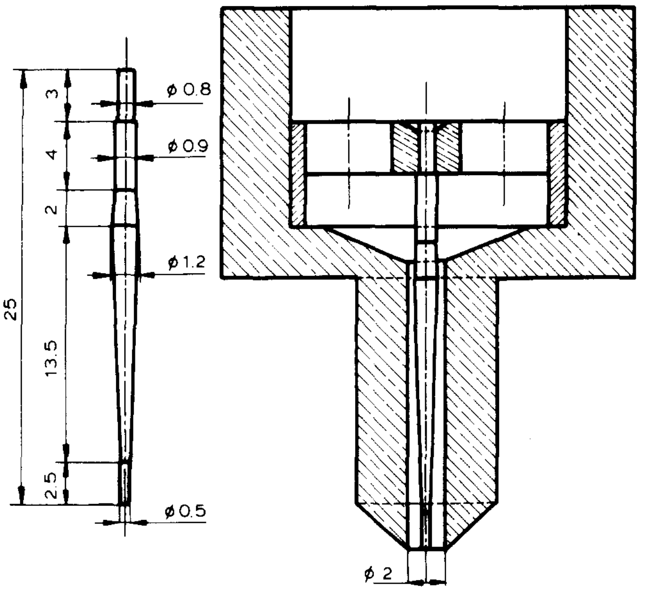

Fig 3 Nozzle with needle laid upon its axial centre line (dimensions in mm)

Nozzle with needle

The 'needle' generator has a very stable mode of operation. The needle used was shaped (Fig. 3) so as to form a sonic throat and provide a supersonic jet. For the area ratio given by this needle and for a diatomic gas, such as nitrogen, the exit jet Mach number is 1.82 and is correctly expanded for $p_{totj}/p_a = 5.92$.

Shutter

The shutter was positioned between the nozzle exit and the tube mouth, and was driven by an electromagnet. Its opening time was short compared with the heating time, which was measured with small thermocouples (a few milliseconds). The opening time was determined with a photoelectric cell whose signal was sent on a Bryans recorder type 515 A (see below); it was found to be less than 0.3 ms.

HS tube shapes

Tubes with various shapes were tested. First, the performances of cylindrical cavities of different lengths were determined. This is the simplest shape to machine and the flow field in the cavity has been extensively investigated[4,6,8,9]. The inside diameter was equal to the nozzle diameter (2 mm) and the lengths ranged from 10 to 60 mm.

Notation

D	Tube diameter
l	Distance between nozzle exit and tube mouth
L	Tube length
p_a	Ambient pressure
p_{totj}	Total pressure of driving jet
t	Time
x	Distance along tube

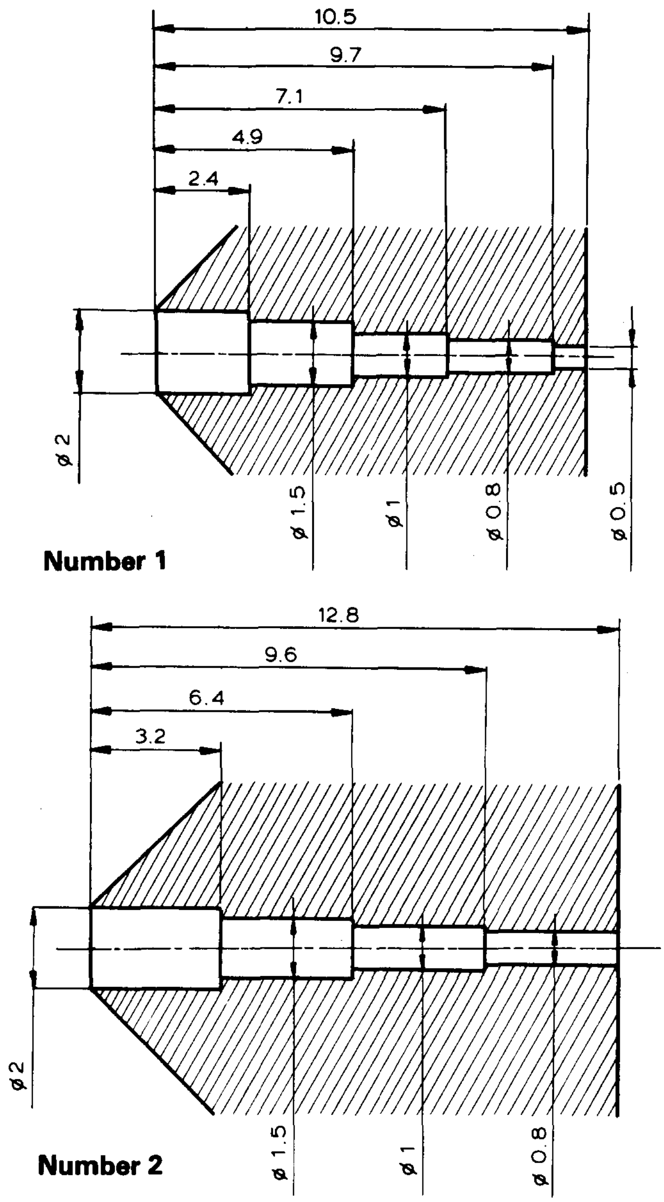

Fig. 4 Stepped cavities (dimensions in mm)

Second, 'stepped' cavities were tested, as was done by Marchese[12]. This shape may be considered as a 'machinable approximation' to a tapered tube. The purpose of the taper is to strengthen the intensity of the shock waves moving down the tube, thereby increasing the heating effects[10,11,14]. The two stepped cavities tested are shown in Fig. 4. Number 1 was an exact reproduction (at a suitable scale) of the cavity SRI-1 used by Marchese (Ref 12, Table 1, p. 41); number 2 was an exact reproduction (also at a suitable scale) of the cavity SRI-2 tested by the same author.

HS tube materials

The thermal characteristics of the tube material influence the heat losses, and this can be very important with small cavities. It is difficult to find a material which, simultaneously, is a good insulator, has sufficient mechanical strength and can be used at high temperatures. Three materials have been tested, as follows.

Durestos. This material is a composite of asbestos fibre and phenolic resin. Its thermal diffusivity is 1.5×10^{-7} m^2/s and its thermal conductivity 0.2925 W/m K. The maximum temperature for continuous use is 180 °C. Although this temperature is quite below the required temperature for ignition purposes (300–700 °C), temperatures as high as 1100 °C have been recorded in some tests (see below) without excessive damage to the cavity.

Wood. When the HS tube is used for one ignition only, wood may be considered as a possible material. Its very low thermal conductivity (about 0.05 W/m K) could lead to substantially higher temperatures, as was demonstrated in the pioneer work of Sprenger[2]. In the present work, azobe wood (a kind of mahogany) was used.

Machinable ceramic. The MACOR ceramic manufactured by Corning has a thermal conductivity of 1.731 W/m K, that is a value six times that of Durestos. Heat losses can be expected to be substantially larger with the MACOR, but for applications in which the HS tube has to be used several times at high temperatures, this material could be considered. A drawback of this material, however, is its great fragility.

Thermocouples.

It has been shown theoretically that very high heating rates are feasible near the end plate of an HS tube. To measure the instantaneous gas temperature, very thin thermocouple wires are required. Thin wires are also necessary to limit heat losses through the wires themselves. In all the tests reported here, 25 μm diameter chromel–alumel wires were used.

As pointed out in Ref 15, the characteristic time of the thermocouple is not a well-defined quantity. With certain simplifying assumptions, a knowledge of the heat transfer[16] permits an estimate of the characteristic time. In the conditions of the tests reported here, the characteristic time of the thermocouples was of the order of 10 ms. Clearly this time is not short enough to indicate the temperature fluctuations at each cycle, since with short cavities, excited by helium for instance, the oscillation frequency is about 30 kHz. Hence the 'instantaneous' temperature recorded by the thermocouple is only a measure of how fast a small amount of material can be brought up to a high temperature at the end wall of an HS tube. Although it is qualitative only, the information is very important in determining the use of the HS tube as an igniter, for instance.

Fast recording system

The recording system used was a Physical Data type 515 A, with up to 20 channels. On each channel the phenomenon recorded could be sampled at a frequency up to 2 MHz, each sample being stocked numerically in a memory with 2048 words.

Experiments

The parameters that play a role in the heating of HS tubes are numerous. The most important ones are;

the pressure of the driving jet
the nature of the gas
the distance l separating the nozzle exit and the tube mouth
the cavity shape
the physical properties of the tube material
the tube size.

The most significant results (out of more than 500 tests) are given below. The influence of the first five parameters has only been tested thoroughly with cavities made of Durestos.

In all the tests, the temperature of the gas supply, the initial temperature of the HS tube and the temperature of the gas contained therein were all equal to the ambient temperature (about 300K).

Influence of driving pressure

The influence of this parameter was tested with stepped cavity (1) and the results are shown in Fig. 5. The temperature increased almost steadily with the driving pressure. Such a characteristic is peculiar to the 'needle' generator since its mode of operation is not linked with the shock cell structure of the jet. A classical HS tube would show peaks and troughs in its temperature as the pressure increased, depending on whether the tube mouth lay within or outside the instability intervals.

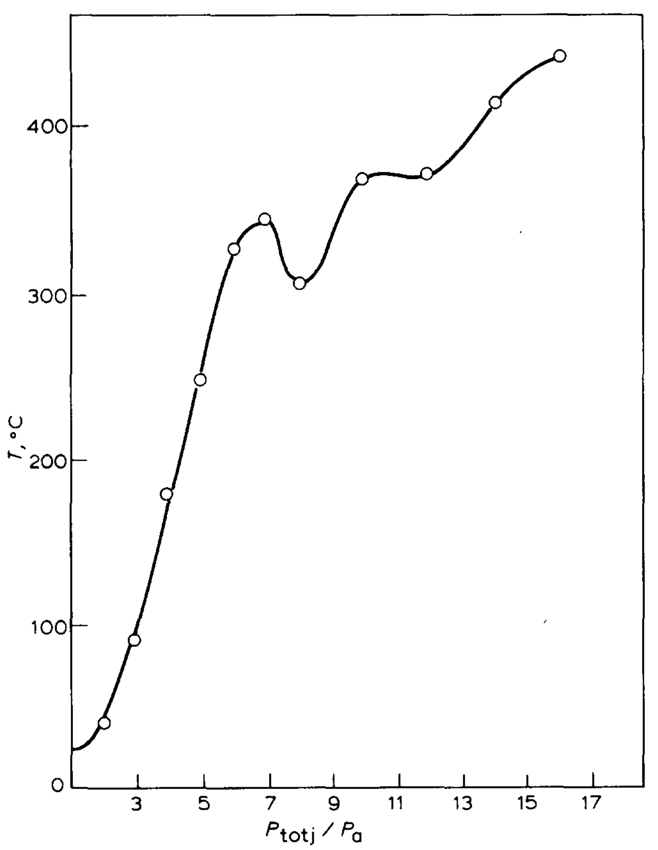

Fig 5 Influence of driving pressure on maximum temperature for stepped cavity (1). The gas is nitrogen, and $l = 6$ mm

For the needle generator, a single peak and trough occurs near the design pressure ratio of the nozzle (5.92).

Influence of driving gas and of separation distance l

It can be shown theoretically that monatomic gases should produce much larger heating effects than do diatomic gases, because, for a given Mach number of the driving jet, shock wave irreversibilities are stronger for monatomic gases. This follows directly from Rankine–Hugoniot shock relations.

Fig 6 shows the measured temperatures for helium, argon and nitrogen, as a function of the distance l separating the nozzle exit from the tube mouth. Helium and argon produce much higher temperatures than does nitrogen, so confirming theoretical results[8]. Also, the heating effects are high over a range of l much wider than is the case for a classical HS tube. The influence of the driving gas is important not only for the maximum value of the temperature but also for the heating rate. This can be seen in Fig. 7, which represents typical tests carried out with the fast recording system. From these instantaneous temperature measurements, it was found that a temperature of 300 °C could be reached:

in 49 ms with nitrogen
in 6.9 ms with argon
in 1.7 ms with helium.

Influence of cavity shape

The measured performances of two 'stepped' cavities (Fig. 4) are compared with the performances of a cylindrical cavity in Table 1. Both stepped cavities produced temperatures substantially higher than the cylindrical one, cavity (1) producing the highest temperature.

More recent work by the authors has shown that stepped cavities have an operating mode similar to that of conical cavities and that the cone angle has a pronounced influence on the heating performance.

Influence of physical properties of tube material

This influence has been tested with cylindrical cavities only. Although this shape does not lead to high temperatures it has the advantage of being easily machined.

The temperatures measured after 100 ms are shown in Fig. 8. As was expected, the material with

Table 1 Temperature measured after 100 ms

Gas	Cavity temperature (°C)		
	Cylindrical ($L/D = 20$)	Stepped (1)	Stepped (2)
Nitrogen	167	372	218
Argon	290	512	327
Helium	480	928	564

Driving pressure = 7 bar

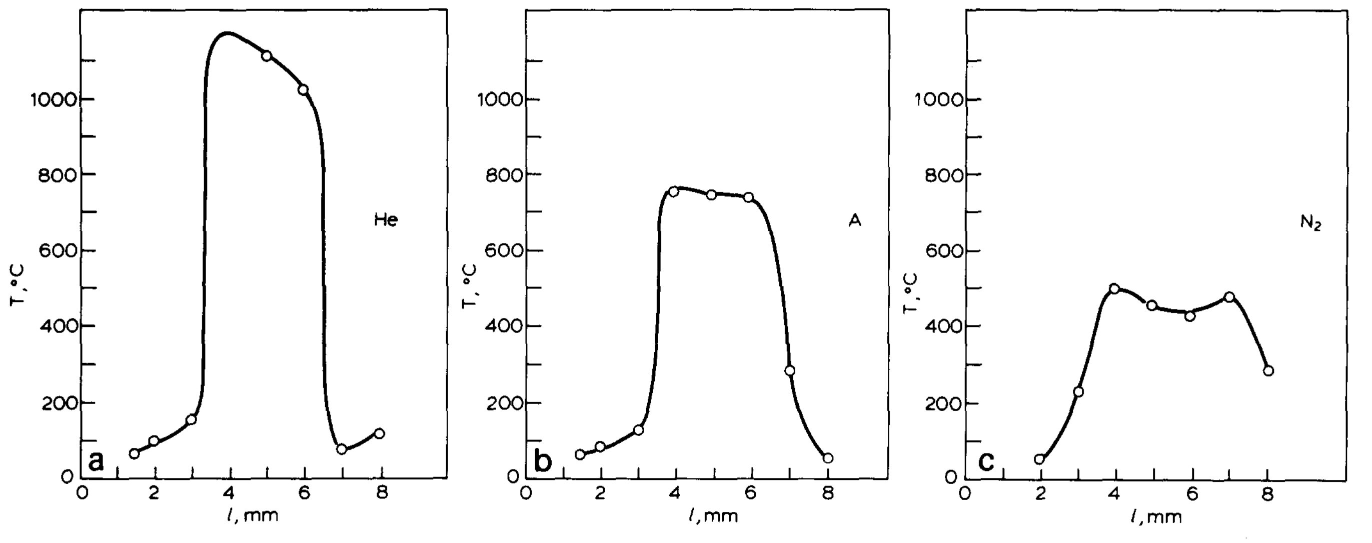

Fig. 6 Influence of gas and of separating distance l on maximum temperature for stepped cavity (1). p_{totj} = *7 bars.*

the lowest thermal conductivity (wood) leads to the highest temperatures.

Conclusions

The 'needle' generator produces temperatures sufficiently high to warrant its application for ignition purposes. Its more stable mode of operation provides a heating performance which is better than that of the classical Hartmann configuration, over a large driving pressure range.

Stepped cavities are capable of higher temperatures than are cylindrical ones, but more recent work by the authors indicates that even higher temperatures could be reached with conical cavities.

Monatomic gases, as expected, produce much higher temperatures than do diatomic gases.

For small tubes the thermal characteristics of the tube material are important. Materials with the lowest heat conductivities, as expected, lead to the highest temperatures.

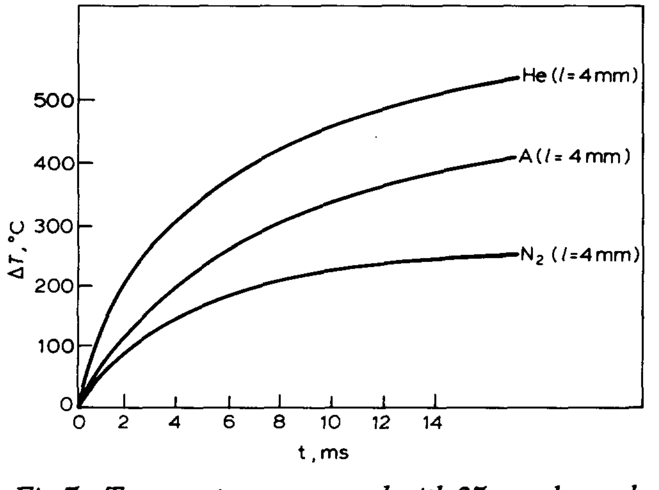

Fig 7 Temperature measured with 25 μm chromel–alumel thermocouple as a function of time for stepped cavity (1). p_{totj} = *7 bar;* ΔT = *thermocouple junction temperature–ambient temperature*

Further research is in progress, particularly on the measuring of the instantaneous heat flux at the end wall of the tube.

Acknowledgement

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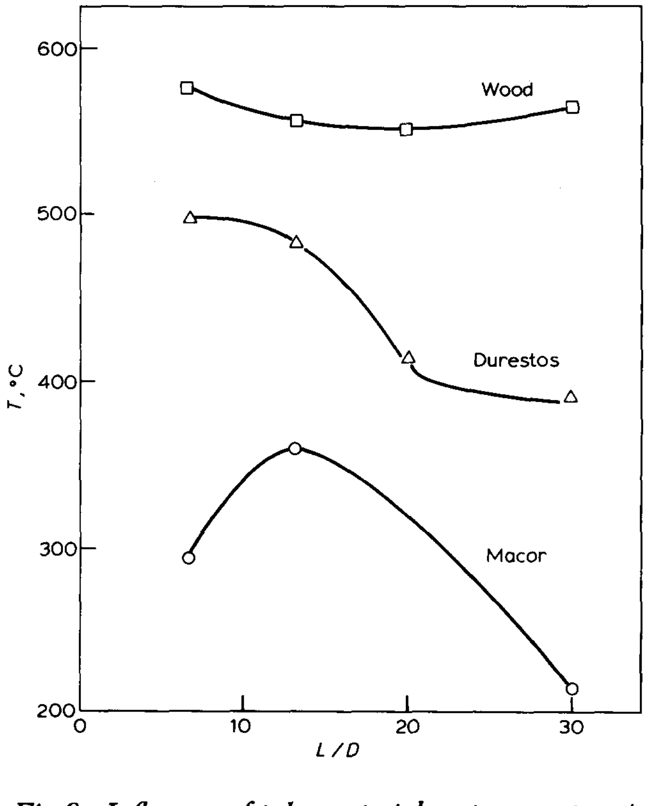

Fig 8 Influence of tube material on temperature in a cylindrical cavity measured after 100 ms. The gas is helium. p_{totj} = *7 bar*

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BOOK REVIEWS

Nuclear Reactor Safety Heat Transfer

Edited by Owen C. Jones Jr

This very large book of nearly one thousand pages claims to be an organised composite summary of nuclear safety heat transfer technology and to describe the state of the art at the turn of the decade (1980's). Many of the authors are internationally recognised authorities in their fields and the book provides valuable information both for the student and seasoned engineer. Each chapter ends with a comprehensive list of references for further detailed study.

We assume that with so many contributors it has been difficult to achieve a reasonable balance. The book is virtually confined to the safety problems of light water reactors (lwr) and liquid metal fast breeder reactors (lmfbr) though it does make brief mention of other types. Table 1.1 (p 5) gives the world list of nuclear power plants operable, under construction or on order up to Dec 1979. There are more than 430 lwr, 50 gas cooled reactors and 7 lmfbr listed and yet the safety problems of lmfbr receive the same attention as those of lwr while gas cooled reactors are not seriously considered.

Chapter 2 deals with power reactor concepts and systems. The introduction admits to an overview of some selected nuclear reactor systems which have been constructed or proposed. As some of the proposed systems are not serious contenders, we suggest that if space was limited it would have been more valuable to restrict the descriptions to only those constructed and to have given more details of the operating pressures and temperatures, pressure vessel and containment problems, and other safety related aspects. Some of this information is given elsewhere in the book but it is difficult to collate all the relevant data.

There are two chapters on Single and Two Phase Flow. Single phase problems are covered in about one percent of the pages and, though this may suggest the relative magnitude of the two groups of problems, the reader would be well advised not to assume that we are knowledgeable in all aspects of single phase flow such as flow distribution and pressure drop in complex manifolds, or in a double ended guillotine fracture.

Two authors virtually repeat the same description of Reactor Operating States that can be usefully categorised for the pressurised water reactor. We are surprised to find no mention of Einstein in a chronological summary of important events in the history of nuclear energy, in an otherwise excellent introductory chapter.

The general quality of the text and figures is good. There are, however, many examples of illegible figures (pp 167, 299, 434) and one curious confusion is in the sketches of reactor types in that the only figure suggesting a substantial primary circuit is for a system operating at close to atmospheric pressure (p 108).

For readers interested in a general introduction to the problems of nuclear reactor safety heat transfer and for the specialist concerned with lwr or lmfbr we can strongly recommend the purchase of this book. Our criticisms, a few of which are listed above, should not detract from a significant publication.

B. N. Furber and Y. L. Sinai
National Nuclear Corporation Ltd

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