DEVELOPMENT OF AN EXPERIMENTAL APPARATUS FOR THERMAL CHARACTERIZATION OF ABLATIVE MATERIALS

Lucas M. C. Arruda
Satellite Thermal Control Laboratory, Department of Mechanical Engineering
Federal University of Santa Catarina
P.O. Box 476 – Trindade – Florianópolis – SC – Brazil.
arruda@labsolar.ufsc.br

Walber Ferreira Braga
Satellite Thermal Control Laboratory, Federal University of Santa Catarina
walber@labsolar.ufsc.br

Marcia B. H. Mantelli
Satellite Thermal Control Laboratory, Federal University of Santa Catarina
marcia@labsolar.ufsc.br

Abstract. *The ablation process undergoing on some materials used for thermal protection of space vehicles during the reentry is a very comlpex phenomenon, difficult to be theoretically analysed. Numerical and aproximated analitical solutions have been proposed to predict the behaviour of these materials during the ablation.These results must be experimentally validated before being used in the design of the Thermal Protection System (TPS). Beside this, extend experimental data for ablative materials are also essential to better understand the ablation phenomenon. A new concept of a simple and reliable experimental apparatus, capable of obtaining data for these materials is described in this paper and represents an important contribuition to the state of the art. The aim of this work is to present this experimental apparatus for the thermal characterization of materials undergoing ablation. The developed apparatus is a low-cost, efficient setup, easy-to-work and easy to calibrate. The main parts of the experimental setup are described and their capabilities compared with other apparatuses already used, presented in the literature.*

Keywords. *Experimental apparatus, ablative materials, ablation, heat transfer.*

1. Introduction

Mathematical models used by Engineers must always be validated by experimental data which can be obtained from different types of experimental apparatuses. This is the case of the ablation phenomenon. The Thermal Protection System's designers use models which need to be validated. Very complex physical phenomena and chemical reactions can be found in materials under ablation, including pyrolisis, oxidation, sublimation, combustion and mechanical erosion (Thimoteo (1986)). Based on the specific model, different overall configurations for the experimental apparatuses have to be employed to capture the physics modeled. On the other hand, some requirements are usually desired to all facilities designed to simulate the ablation phenomena: they must supply a high heat load to the sample, they should present easy heat output control, they should be an easy-to-work facility and should provide an efficient inert or reacting atmosphere over the sample.

Ablating materials respond differently for different heat loads. The capability of capturing the high temperature gradients and the variable thermophysical properties nature of the material is very important for accurate experimental tests in ground ablation facilities, that simulate real flight conditions.

Ablative materials development for TPS has been stimulated by the Brazilian Space Agency (AEB) in order to grant theoretical and experimental capability for the National Program of Space Activities (PNAE). Although some experimental facilities have been already built in the international scientific community, there is still a lack of extend data of thermophysical properties for ablative materials in literature (Braga (2002), Thimoteo (1986)). These needs led the Satellite Thermal Control Laboratory (NCTS) to design a new concept of experimental facility which is flexible, being able of simulating different ablation conditions by the variation of the heat load over the sample. Comparing with some others apparatuses, the developed setup is low-cost and capable of obtaining reliable results to estimate thermophysical properties and to validate mathematical models, including one developed by the laboratory (Braga (2002)), for one-dimensional heat transfer with constant heat flux.

2. Literature Review

In Laux *et all*. (1998) paper, a laser heating facility in Japan using non-reacting atmosphere is compared with the Plasma Wind Tunnel of the Institut fur Raumfahrtsysteme (IRS), in Germany, for thermal verification of ablative materials. Both concepts offer a high energy output, on which is possible to simulate a non-reacting and strong reactive atmosphere. In the case of the plasma wind tunnel, a high mechanical load can be obtained by the consideration of the gases ionization. However, these facilities and equipments are considerably expensive and therefore are not available for most researchers.

On the other hand, Silva (2001) describes a low cost and standardized concept which is more commonly employed and that is based on an oxy-acetylene torch as described by ASTM E285-80. However, it has some limitations such as easy and accurate control of the heat source. The control is through a valve located before the gas mixing chamber. In this situation, it is not possible to use an inert atmosphere and the oxidation and combustion phenomenon must be considered. The accurate relation between theoretical models and experimental results can no longer be expected, unless the model includes these phenomena. The heat load obtained in the present work is not yet as high as that obtained by the two concepts described before.

An experimental apparatus, with a cone heater as the heat source, has been described by Atreya et all. (2002) where the heater provides a global heating for the sample, making possible a less accurate study of one-dimensional heat transfer along the material.

Another ground test facility is described by Hilfer et all. (1998), where a xenon lamp is used as the heat source. A mirror is used to focalize the light over the sample top surface, allowing a significant heat concentration. The optical project, however, considers no collimation of the light and there is no chance to approximate the radiation profile on a transversal section of the specimen by a homogeneous distribution.

The new concept described in this work is a relative low-cost apparatus for ablation tests using inert atmosphere and an easy-to-control heat source system. The heat flux concentration on the sample is achieved by focusing the energy of a 2000W short arc Xenon Lamp on the sample by optical adjustment of two quartz lenses and a high temperature special mirror located over the lamp. This mirror works in order to maximize the optical efficiency and the quartz lenses are used to leave an approximated homogeneous radiation profile over the sample. This configuration allows the heat load to be focalized on one face of the sample, improving the one dimensional ablation condition which is considered in the mathematical modeling developed at NCTS by Braga (2002). The sample is put inside a vacuum chamber, ensuring that the out gassing products from the ablator are discharged with no reacting atomic or molecule particles.

3. Problem description

3.1 Ablation Process

Ablators can be basically divided in two major groups: pure and composite materials as described by Braga (2002) and Kanevce (1999). Pure ablative materials are mainly characterized by no phase changes at the surface until it reaches the ablation temperature. Once at this temperature, the material sublimates absorbing heat from the heat source. Composites are usually made of a fiber matrix and resin, and can be described during the ablation process by three distinct regions. In the first one, the material has not achieved the pyrolisis temperature. In the second, the pyrolisis is taking place, which is a chemical or physical reaction that occurs by an elevated temperature as the sublimation of the resin, and the last one where the gas specimen, resulted from the pyrolisis in the second region, are been conducted outwards. This last and boarder region of the heat shield is called “char” and is basically composed by the fibrous matrix that forms a porous medium, which is a function of the local pressure and of the heating rate (Torre et all. (2000)). Figure (1) shows the basic scheme of ablation on pure (Fig. 1a) and composite materials (Fig. 1b) for constant heat flux and thermophysical properties.

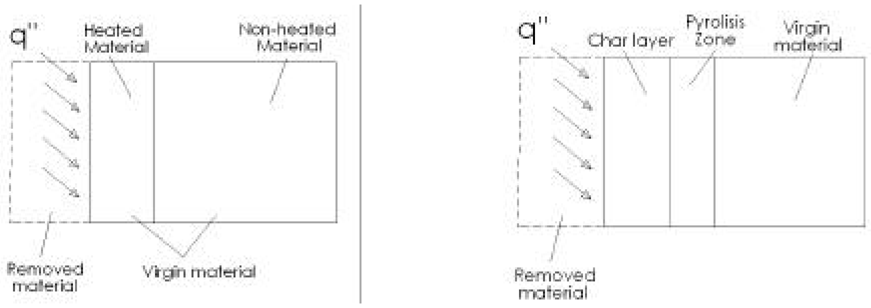

Fig. 1a

Fig. 1b

Figure 1. Model of ablation on pure material (Fig. 1a) and ablation on composite materials (Fig. 1b).

Experimental facilities must also take into account the origin and type of heat transfer taking place on the ablator. When a spacecraft is entering the atmosphere, some specific heat transfer conditions will predominate over others. This is a function of the kind of flow over the body surface and this flow is function of the velocity of the re-entering body. Low orbit satellites face specially convection heat transfer over the ablative material during re-entry. At these conditions, radiation is not a significant fraction of the heat load imposed to the ablative shield (NASA (1971)). Spacecrafts at velocities in the order of the lunar-return (11000 m/s) face the ionization of the flow surrounding the surface (NASA (1971)), and are subjected to very high heat loads where the radiation is a significant part of the heat flux. Another phenomenon to be considered is the spallation process, investigated by Laux et all. (1998). It occurs in solid particles containing carbon that reaches the inviscid region of the flow where temperatures are very high. The vaporized particles release carbonaceous gas specimens, which function as strong radiators. In this case, radiation is strongly significant and may be the cause of discrepancies between predicted ablation rates and data, from real flights, as described by Laux et all. (1998).

By using vacuum environment in the experimental analysis, only radiation heat transfer will occur and no spontaneous ignition in ambient air will take place, according to Atreya et all. (2002). This phenomenon produces a local flame, which changes the boundary conditions required for modeling and affects the control of the heat transfer over the sample, by adding different heat sources as radiation from combustion gases.

3.2 The heat source

A 2000W xenon lamp is used as the experimental heat source. This kind of pulsed short arc lamp emits radiation specially in the UV range of the spectrum. The use of UV is justified by the presence of this radiation in real conditions during re-entry, particularly at high re-entry velocities, usually above 11000 m/s NASA (1971). When ionization is taking place in these conditions, ultraviolet rays are emitted, having a special influence in the ablation process, once these rays are suspected to affect the oxidation phenomena on ablative materials (Hilfer et all. (1998)), resulting in significant erosion of the ablator.

Besides, the use of a radiative profile to heat the sample is the easiest and most accurate mode of ensuring constant heat flux over the ablator.

4. Experimental Apparatus

The new concept can be basically overviewed in Fig. (2). It involves a heat source from which the radiation is directed to the top face of the sample by quartz lenses. The ablative material itself is set inside a vacuum chamber. Five thermocouples are installed along the center line length of the material. A feed-through system, set on the bottom of the chamber is used to connect the sensors to the data logger. This equipment is coupled to a computer, where data can be recorded. The exit to vacuum pump is located on the bottom of the chamber. By its side, a pressure control command valve is installed as a safe valve, used in order to keep the pressure inside the chamber bellow its maximum limit. This limit is calculated to keep the integrity of the 2nd quartz lens which also works as the chamber window for the incoming radiation.

The heat source assembly involves refractory bricks and a high temperature mirror. Each part will be described further.

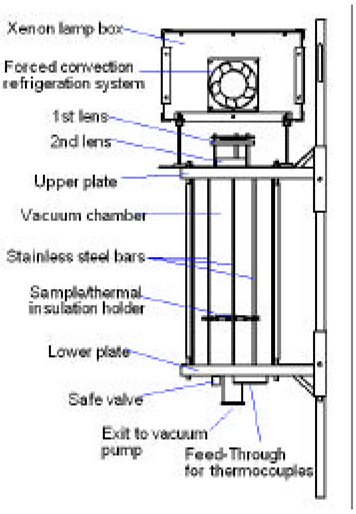

Figure 2. Basic scheme of the experimental setup.

4.1 The chamber

The vacuum inside the chamber disables any spontaneous air ignition, ensuring the predicted heat flux over the sample. The upper part contains one quartz lens that works as a window for the incoming radiation. Its purpose in the optical project will be described further.

Both upper and lower plates are made of stainless steel and are rubber sealed with a cylinder made of the same material. Three thin stainless steel bars connect the plates in order to support the sample holder. This is show in Fig. (3).

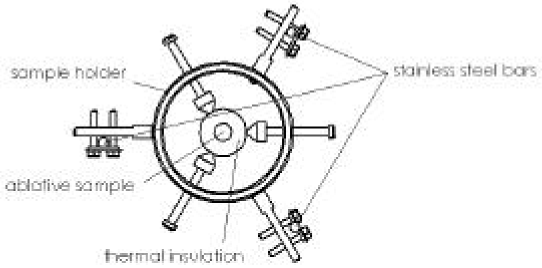

Figure 3. System for sample holder.

The thermocouples feed-through system, shown in Fig. (4), is made of a solid copper cylinder, that is vacuum sealed with epoxy resin.

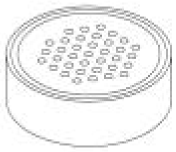

Figure 4. Feed-Through for thermocouples.

The quartz window dictates the maximum pressure allowed inside the chamber during the experiment, which is of 150000 Pa. Therefore, a safe valve is connected on the lower plate in order to keep lower pressures inside it. This pressure release system is set with this solenoid valve, driven by a pressure controller.

4.2 The sample

In order to analyze an one-dimensional ablation problem in the sample, a thermal insulation is used according to the scheme presented in Fig. (5). Bakelite was used as the thermal insulator and is designed to provide good fitting. The thermocouples are assembled at the sample centre line along its length, where the highest heat flux is expected due to the concentric radiation profile of the xenon lamp. Thermocouple #1 is set on the front face of the sample and #5 is set on the rear face of the specimen. Others are assembled within the specimen, leaving 1mm from each other. The sample has a diameter of 10mm and 4mm of thickness.

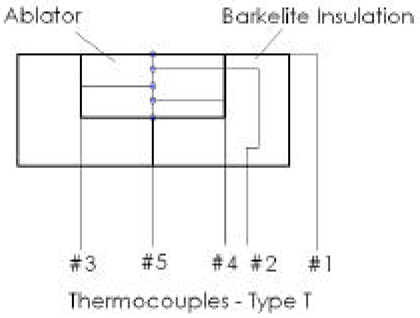

Figure 5. Thermocouples assembling – ablator/thermal insulation fitting.

4.3 Optical Project

The first lens is assembled close to the lamp in order to increase the optical efficiency by using the highest solid angle possible from the radiator filament of the lamp (distance between cathode and anode) to the quartz lens. The second lens focalizes the radiation in direction of the front surface of the sample. The optical schematic can be seen in Fig. (6).

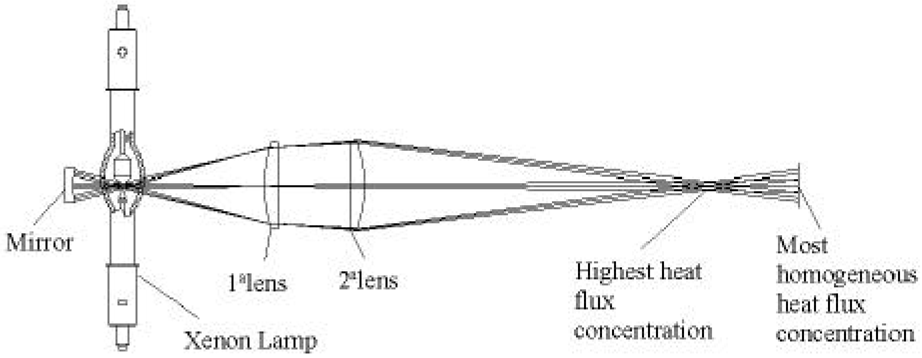

Figure 6. Optical layout.

The use of quartz is justified by its strong relation between transmissibility to UV radiation and mechanical resistance, among a vast variety of other glasses. Although some different materials are available in the market, *“Suprasil”* was used, because it offers high transmissibility for the UV radiation range from xenon lamp, compared to the others and also has a smaller cost.

4.4 Heat source and auxiliary equipments

Figure (7) shows the holders of the heat source system and the high temperature mirror set over the lamp. Its position is very important since it reflects the radiation back against the ionized radiator filament of the lamp. The centre of the filament must stay at the centre of curvature of the mirror to ensure that the reflected radiation will not irradiate on the cathode, neither on the anode. This would cause the overheating of these parts and consequently the reduction of the estimated average lamp life.

During ignition, lamp requires 33 kV, provided by the lamp reactor shown in Fig. (8). For this reason, the metal parts of the lamp box must stay at safe distances from the metal head of the high voltage cable, to avoid parasite current in the box. The relation distance/voltage required is 1mm/kV which leads to, at least, 33 mm in this case. This is guaranteed by common refractory bricks as shown in Fig. (7).

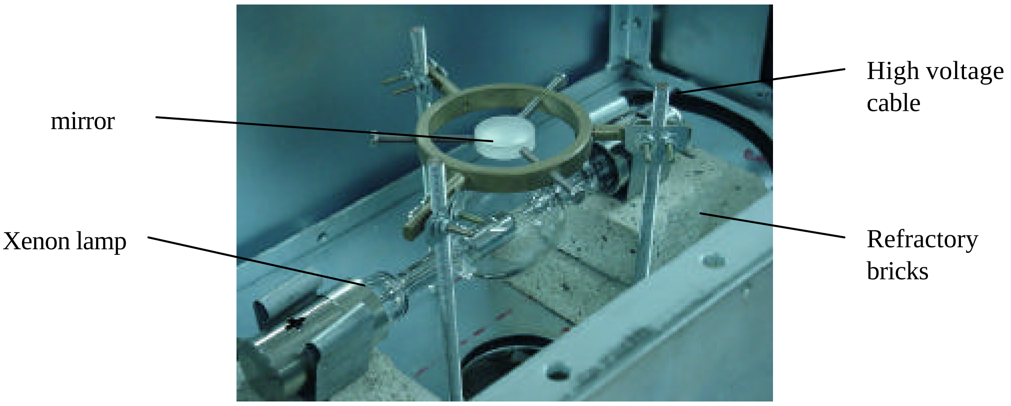

Figure 7. Optical assembly – lamp/mirror.

5. Adjustments

In order to control better the heat load over the surface of the sample, the 1st lens and the lamp box should be aligned. By changing the distances of both lamp box (and therefore the radiator filament of the lamp) and first lens, different radiation profiles are possible, as the result of the diameter of heated material over the front face of the specimen. As mentioned earlier, the mirror must be fixed and, therefore, it does not contribute to changes of the heat load distribution.

Radiation load over the sample can still be changed by introducing an electronic dimmer, which can be controlled by the computer, to regulate the working voltage of the lamp. This will affect its luminosity and hence the heat flux arriving on the ablator. An overview of the apparatus is shown in Fig. (8).

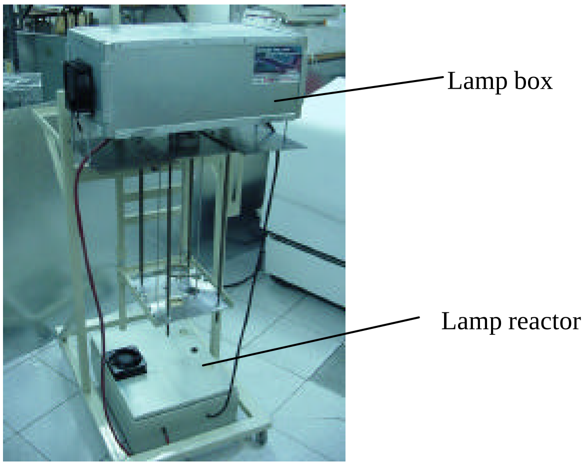

Figure 8. The experimental apparatus at NCTS.

6. Concluding Remarks

The new experimental facility has been built at the Satellite Thermal Control Laboratory (see Fig. (8)), and is currently under heat load and calibration tests. It has proved to be a relative low-cost and simple experiment, which allows accurate estimation of the heat flux arriving on the specimen and good thermal insulation of the sample for one-dimensional heat transfer treatment. Some tests are being currently conducted to enable the calibration and the prediction of the temperature acquisition uncertainties, to acknowledge the tests restrictions, to evaluate the thermal contact resistance between the thermocouples and the material inside the sample, to obtain the response time accuracy of sensors and to determine the thermal losses of the heat source assembly.

7. Acknowledgements

The authors wish to acknowledge CAPES through the project PROCAD and CNPq for providing the scholarship support, which made this work possible.

8. References

Atreya, Arvind and Agrawal, Sanjay, 2002, "An Experimental and Theoretical Investigation Into Burning Characteristics of PPS-Glass Fiber Composites", 8th AIAA/ASME Joint Thermophysics and Heat Transfer Conference, AIAA 2002-2887, St. Louis, USA.

Braga, W. F., 2002, "Método Integral e de Analogia Elétrica para a Solução de Transferência de Calor Unidimansional de Sólido com Ablação", Thesis, UFSC, Department of Mechanical Engineering, Florianópolis, Brazil.

Hilfer, G., Auweter-Kurtz, M., Morino, Y. and Yoshinaka, T., 1998, "On the Oxidation Behaviour of C/C-Materials for Thermal Protection Systems, 3rd European Workshop on Thermal Protection Systems, Noordwijk, Holland.

Kanevce, Ljubica F., Kanevce, Gligor H., 1999, "Comparison of Two Kinds of Experiments for Estimation of Thermal Properties of Ablative Composite", 3rd International Conference on Inverse Problems in Engineering, Port Ludlow, USA.

Laux, T., Auweter-Kurtz, M., Wegmann, Th., Morino, Y., Yoshinaka, T., Park, C., Speckmann, H.-D., 1998, "Comparison of Ablation Material Testsin a Plasma Wind Tunnel and Laser Heating Facilities", 3rd European Workshop on Thermal Protection Systems, Noordwijk, Holland.

NASA, NASA SP-8062 Entry Gasdynamic Heating, 1971, Available at http://www.nasa.gov on Oct. 2002.

Silva, D. V. F. M. R, 2001, "Estimativa de Propriedades Térmicas de Materiais Ablativos", Thesis, UFRJ, Department of Mechanical Engineering, Rio de Janeiro, Brazil.

Thimoteo, Hilzete P. C. A., 1986, "Estudo do Comportamento Ablativo de Composições Fenólicas com Carga", Thesis, UFRJ, Rio de Janeiro, Brazil.

Torre, L., Kenny, J. M., Boghetich, G., Maffezzoli, A., "Degradation Behaviour of a Composite Material for Thermal Protection Systems", Journal of Materials Science, 35, 2000, pp. 4563-4566.