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Experimental study of heat transfer in a water film exposed to a radiant flux. Application to thermal protection of composite walls

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ABSTRACT

The following work is dedicated to assessing the performance of a falling water film as a thermal protection for composite walls exposed to a radiant flux. For this purpose, an experimental set-up was designed. The water film is created by spray nozzles and flow rates lie between 120 and 880 kg/hm$_{wall}$. Different radiant flux steps from 1 to 5 kW/m^2 are tested. Temperature is measured at different locations inside the composite panel and at the water inlet and outlet. Three different experiments are considered: one without water film, to serve as a reference, another where the composite and the film are exposed to the radiant flux without initial heating, and finally a wall at 100 °C before the film is triggered. The film shows a good capacity to cool and to protect the wall in the range of this study.

1. Introduction

New material research is a very active field. It represents for many industries the key to economic and energetic optimization. The maritime sector, for example, is radically impacted with developments of high performance composite materials. Their use provides weight, stability and energy consumption improvements to name but a few. However, despite suitable structural properties, some particular composites (based on fiber reinforced polymers) emit toxic fumes when submitted to important temperatures. Thus, they cannot be allowed for a number of internal applications for regulatory reason in case of fire [1].

Exception to this regulation can be made if a heat protection device is proved to prevent combustibility. This has motivated the present work. It is dedicated to the study of a water film based system. The idea is using important heat exchange with liquid film, when a vertical composite panel is submitted to a radiant heat flux.

Water films are indeed used in many thermal applications. They are found for example in seawater desalination device [2] or in the cooling systems of electronic components [3]. They are also used in the context of fire protection of oil tanks [4], glass [5] or metal walls [6]. Excellent heat removal properties were exhibited in these studies even for small water quantities. It is mostly done by convection. The high value of latent heat also allows a large amount of energy to be evacuated through vaporization. Finally, water semi transparency property leads to important radiation absorption capacity (in the infra-red mainly).

Despite the numerous studies concerning water film, its use in wall protection is still fairly limited to feasibility analysis and most often in unidimensional situations. This constitutes a lack of information for the development of protection device using water film.

This article proposes an experimental study of the thermal protection of a composite wall by a water film when submitted to a radiant heat flux. For this purpose an experimental test bench was developed. It allows the protection provided by the film along the wall to be studied for different flow rates and radiative heat fluxes. In order to cover a wide range of possible applications, three different experiments are tested when the wall is submitted to radiation.

2. Materials and methods

2.1. Wall description and instrumentation

In order to investigate the protection provided by the water film, temperature measurements are made inside the composite wall. Dimensions are 2.80 m height and 0.5 m width (noted respectively L and l). A cylindrical sample of the material is presented on Fig. 1. It is formed of a 40 mm thick core in balsa wood and of two skins of polyester resin and fiberglass (3 mm each) arranged on both sides. A total of 7 similar cylinders (20 mm diameter) was taken from a small sample of composite. In such pieces, a proper

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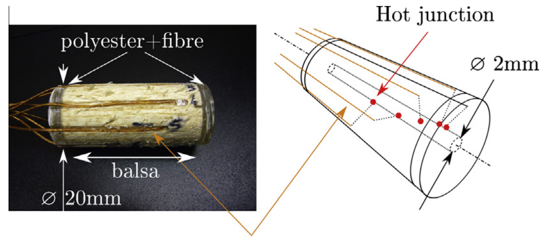

Fig. 1. Photo and schematic representation of a cylindrical sample of the composite wall equipped with thermocouples.

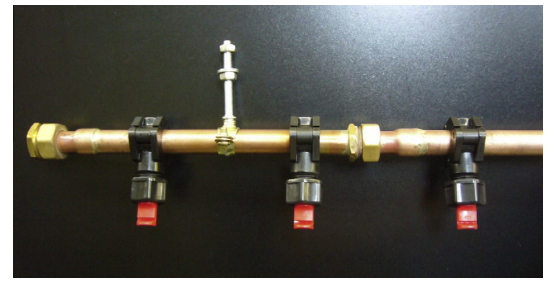

Fig. 3. Photograph of the water injection ramp equipped with three fat spray nozzles.

positioning of thermocouples at different depths is made easier. Holes are drilled in radial direction and staggered in a helical (45°) in the direction of cylinder length. The depth is limited to 9 mm, to avoid hot junctions alignment. K-type thermocouples are set in the composite at: 1, 2, 4, 8, 14, 24, 34 and 45.5 mm respectively to the side exposed to radiant flux. The temperature "probes" are then introduced into the composite test wall in a hole matching precisely the cylinder diameter. Sealing is ensured by a similar polyester resin.

Temperature "probes" were distributed on the test wall according to the scheme shown in Fig. 2. They are separated vertically with 42.5 cm (noted e) and spaced alternately horizontally around the center of the wall to reduce their number, while retaining the ability to observe three-dimensional phenomena ($c = 2.5$ cm).

2.2. Experimental apparatus

The test bench developed for this study is schematized in Fig. 2. Water is supplied by a centrifugal pump from a constant level tank. Flow rate is measured through a Coriolis flowmeter. The water film is created at the top of the wall by three flat spray nozzles (LECHLER, see Fig. 3). It is driven to the bottom of the plate by gravity. Water temperature is measured in the tank and also down the wall in the center of it (see the thermocouple position in Fig. 2).

The radiant heat flux is produced by 60 heating elements (250 W each) made of 904L stainless steel. The emissivity of such alloy is 0.9 at 200 °C and 0.97 at 500 °C [7] and can thus be considered to behave like a black body. A reflecting panel located behind aims to concentrate most of the radiation towards the test wall. Deflectors are used to avoid water projection on electrical connectors (see Fig. 4). The assembly is placed on a pivot. Note that in the later picture, heating elements are not oriented toward the test wall to facilitate the visualization. A sliding steel panel placed between the heating elements and the test wall is used to create steep steps of radiant heat flux. Finally, radiant heat flux density is measured on the wall by a CAPTEC fluxmeter and the corresponding surface temperature of the heating elements was measured by a thermocouple.

Fig. 5 presents the heat flux density received by the wall for different electric powers. Values are displayed as a function of height in the center of the wall only. The corresponding surface temperature of the heating elements are respectively 261, 340, 366 and 467 °C when the mean heat flux increases. Variations of radiant heat flux density at the top and the bottom of the wall can be noticed. They can be logically interpreted as a consequence of the view factor which decreases at these points. Nevertheless, for high radiant heat flux densities, fluctuations can be highlighted in the center of the wall. They can be explained by local differences in ohmic resistances of heating elements. They have been measured and standard deviation is non-negligible: 5.5 Ω.

This test bench enables us to study the effect of a water film flowing on a composite wall exposed to a radiant heat flux. Tendencies at high heat fluxes may be slightly influenced by the radiant heat flux non-homogeneity, but material conductivity tends to soften this effect.

2.3. Experimental procedure

Three different experimental categories were carried out. For each of them, the radiant heat source is used in steady state. This means heating resistances are powered at first and only once they

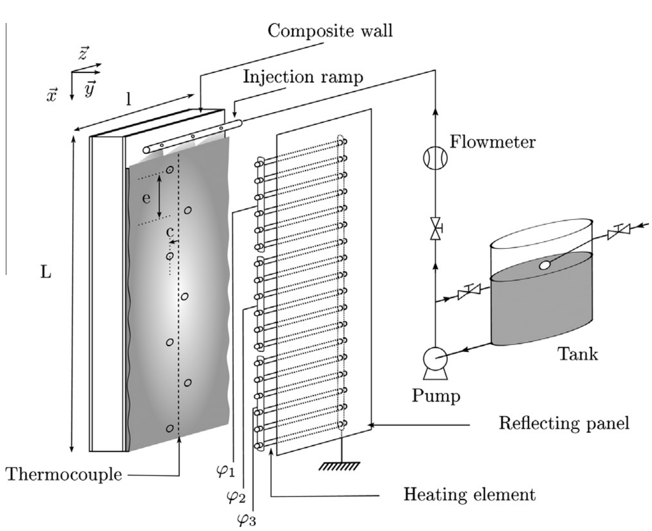

Fig. 2. Schematic view of the experimental test bench.

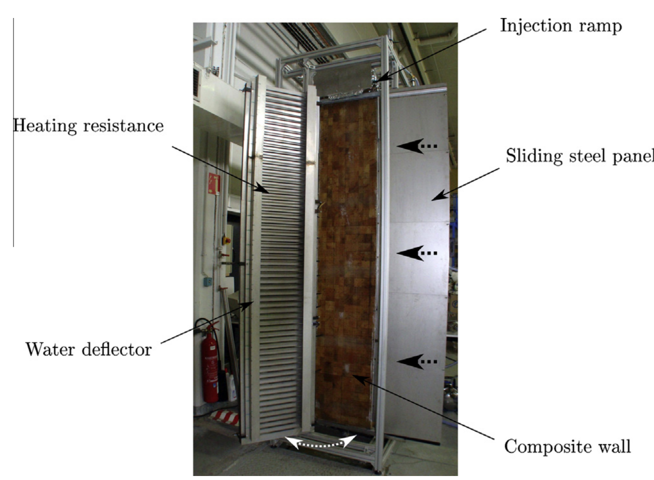

Fig. 4. Photograph of the experimental test bench.