Experimental and numerical study of the effects of equivalence ratio on an air-kerosene diffusion flame impinging a composite material.

R. Ogabi[1], B. Manescau[1], K. Chetehouna[1] and S. Senave[2]
[1]INSA Centre Val de Loire, Univ. Orléans, PRISME EA 4229, F-18022 Bourges, France
[2]DAHER, 41400 St Julien de Chédon, France

**Corresponding author: raphael.ogabi@insa-cvl.fr*

Abstract

In the field of aeronautics, there are several catastrophes related to fire, one of the most devastating is the fire in full flight. Indeed, aircraft accidents leading to fires are often fatal and cause a lot of losses both human and material. Moreover, in the context of reducing manufacturing costs and the use of aircraft, they are still subject to optimization in energy performance. For this, the composite materials used in their design are the subject of research and development. Composite materials have good mechanical properties but have drawbacks when subjected to fire. In this scope, before being used in aircraft design, composite materials are subjected to certification tests for fire resistance based on the standard ISO 2685. These tests are carried out using the FAA standard NexGen burner. In addition, so that the fire test meets the criteria of the standard ISO 2685, the flame must have a temperature of 1100 °C ±80 °C and a heat flux of 116 kW / m^2 ±10 kW / m^2. In this context, the air / kerosene mixture must be made in the right proportions with good conditions of temperature and pressure. In this study, the equivalence ratio is calculated from the mixture between air and kerosene. The objective of this work is to highlight experimentally and numerically the effect of the equivalence ratio on the dynamics of the air / kerosene flame used for the standard tests. The numerical calculations have been carried out using the CFD, FDS code and experiments carried out with the NexGen burner. A validation study showed a good agreement between numerical and experimental results and highlights the capability of FDS to simulate the reactive flows of an air / kerosene diffusion flame. Subsequently, from the numerical and experimental results, it is shown that the flame meets the criteria of ISO 2685 for an equivalence ratio about 0.79.

Keywords: *Equivalence ratio, FDS, Impinging flame, NexGen burner, Infrared visualization.*

1. Introduction

Over the last 50 years, the aeronautics and aerospace industry has made extraordinary progress in optimizing the materials used in the design of the various flying vehicles. Indeed, with great momentum at the research and development level, they have highlighted the advantages of using composite materials as major elements in the manufacture of airplanes and space rockets.

Focusing on aeronautical and aerospace applications and in the event of an airplane fire in flight or a spacecraft entering the Earth's atmosphere, flames impacting these flying vehicles are subject to environmental conditions. Indeed, depending on the altitude and the speed of descent, the flames around composite structures depends on the equivalence ratio. Equivalence ratio represents the air / fuel mixture and it has a great influence on the combustion rate [1][2][3][4][5]. The various studies dealing with the fire behavior of composite materials seek to highlight thermochemical parameters such as the quantity of gas produced during the flame wall interaction. There is also the temperature transmitted by the composite material. The different tests are carried out according to the criteria of

ISO standards. By putting themselves on the criteria of standard, the fire behavior of composite materials according to the equivalence ratio is not studied.

Therefore, the objective of this work is to highlight the effect of equivalence ratio on the fire behavior of composite materials used in the aeronautical and aerospace industry. Firstly, the kerosene flame was first characterized by examining its temperature, heat flux density and the optimum sample position away from the burner. After this, three composite materials will be used including composite materials in Carbon-phenolic, Carbon-PEKK and Carbon-BMI. This study is both experimental and numerical. The experimental part is made from the NexGen burner developed as part of this work and the numerical part is realized using CFD code FDS 6. A description of the NexGen burner is provided in Section 2. In section 3, the results and discussions resulting from this study will be presented and the conclusion will be addressed in section 4.

2.0 Description of the experimental setup and composite material samples

2.1. Thermocouple tree installation

During the experiments, an installation of a thermocouple tree consisting of two sets each of 17 horizontal and vertical thermocouples placed 2.5 cm away from one another such that the first thermocouple was positioned at 10 cm from the burner cone and 25.4 mm above the centerline of the burner cone. The flame temperature is then measured by a data acquisition device with a software program known as lab-view connected to the K-type thermocouples having a diameter of 1/8 inches.
Similarly, the heat flux device called Captec was used to measure the heat flux density of the flame by placing the device containing a very sensitive heat sensor 10 cm in the direction of the flame according to the FAA specified standard.

2.2 NexGen Burner setup

The experimental design that led to the experimental tests is the next generation fire burner (NexGen burner), designed by the FAA (see Figure 2). It allows large-scale testing in accordance with fire protection standards used in the aerospace industry (ISO 2685 and FAA AC20-135). This is a test stand designed to perform certification tests. The tests must be representative of realistic fire conditions, close to those encountered in real-life accidents, particularly when they occur around aircraft engines. In this study, the samples were exposed to an air / kerosene diffusion flame for 15 min with a flame distance of 100 mm. This is the duration recommended by the standard 2685 and the optimum position was determined from the preliminary flame characterization test carried out. Under the standard conditions, the incident flame must provide a heat flow of 116 kW / m² ± 10kw / m² and an average flame temperature of 1100 ° C ± 80 °C [11] [7]. In this study, the tests will not be performed solely according to the criteria of the standard. There will be other configurations that will be related to the value of the equivalence ratio of the flame.

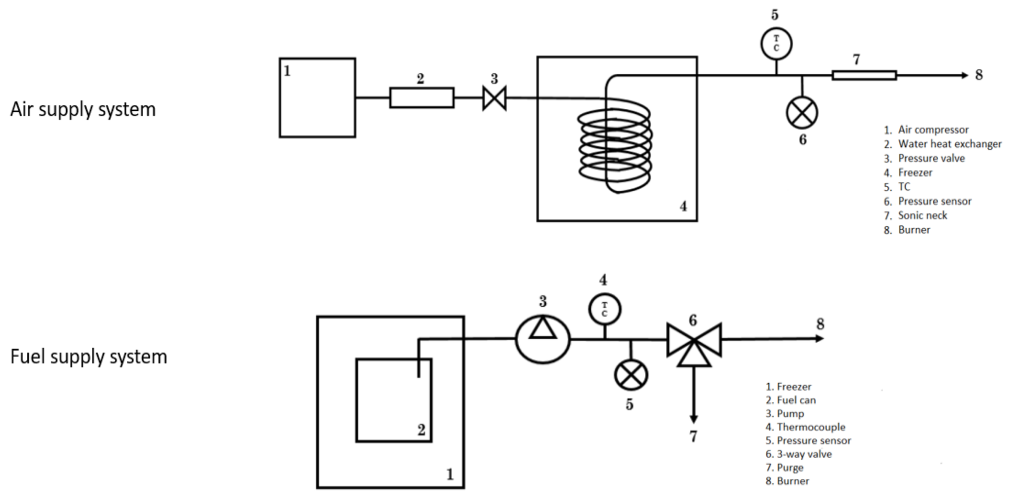

Fig 1. Schematic diagram of the air/fuel supply system

The air supply circuit (see Figure 1) allows the burner to be supplied with air pressure from 2.15 to 4.15 bar via a compressor. The air is regulated by a manual valve. The air then passes through a water exchanger that allows it to cool down for the first time. It then circulates in a coil that is stored in a freezer, ensuring an inlet temperature in the burner between 5 and 15ºC.

Jet A-1 kerosene is used as fuel. This kerosene is the reference fuel for turbojets and turboprops in commercial aircraft [14]. It has a minimum combustion energy of 42.8 MJ.kg-1, a density at 15°C between 775 and 840 kg.m-3[14]. It mainly consists of a mixture of hydrocarbons ranging from C8 to C16 [15]. The fuel supply circuit consists of a 25 L storage canister kept cold in a freezer (see Figure IV-4). This makes it possible to provide a fuel temperature between 0 and 10°C at the level of the injector. The kerosene flow is ensured by a variable flow pump.

2.3. Composite material samples

In this study, four plate samples were used to highlight the effects of the equivalence ratio on the flame wall interaction. A steel plate was used to evaluate the ability to FDS code to simulate the temperature and heat flux fields received by the plate [6]. The three composite materials used are composed of carbon-reinforced matrices that have been cured with pre-impregnated fibers.

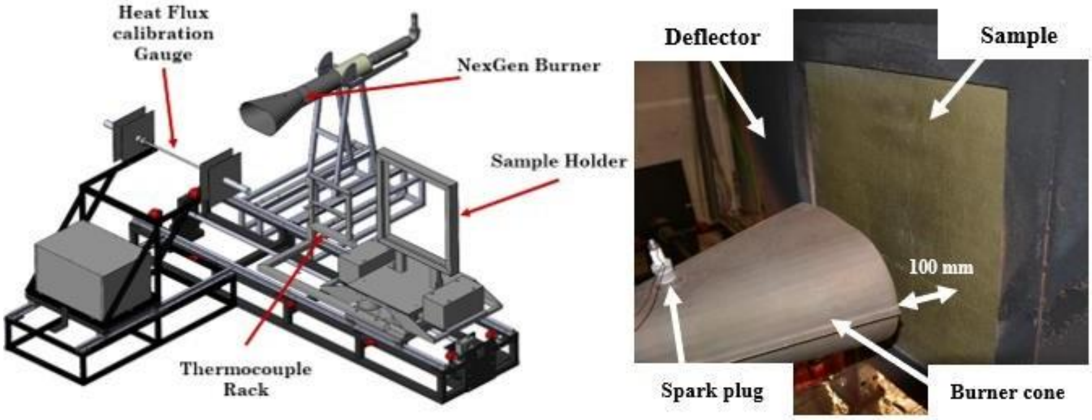

Fig 2. Experiment set up: NexGen Burner

Table 1. Air flow variation

S/N	Air Pressure (bar)	Mass flow rate (Kg/s)	Equivalent ratio
1	2.15	0.02323	0.50
2	2.30	0.02435	0.77
3	2.45	0.02547	0.80
4	2.75	0.02770	0.86
5	2.85	0.02845	0.89
6	3.05	0.02994	0.96
7	3.45	0.03069	0.98
8	3.15	0.03293	1.03
9	3.60	0.03405	1.06
10	3.85	0.03591	1.15
11	4.15	0.03815	1.20

In this study, fire tests were conducted by varying the air flow rate at a constant fuel flow rate of the cone burner assembly (as shown in table 1). Tests were conducted under three different test conditions: a higher airflow case (fuel lean condition), a lower airflow case (fuel rich condition), and a stoichiometric condition. The total test time for flame temperature measurement is 3 minutes (including 30 seconds pre-test process, 2 minutes actual test and 30 seconds post-test process. The following processes were observed: ignition, propagation, yield point and extinction.

These materials were manufactured and supplied by the company DAHER. There are carbon-BMI matrix, carbon- phenolic matrix and carbon-PEKK matrix. Of the three composite materials, two are thermosetting, namely the carbon-BMI matrix and the carbon-phenolic matrix, and the third matrix is thermoplastic- PEKK carbon. The samples are represented by 50cm x 50cm plates. At the level of the thermosetting matrices, the carbon-BMI matrix consists of 6 folds of carbon-BMI with a thickness of 1.5 mm for a mass fraction of 40% fiber and the carbon-phenolic matrix consists of 6 layers of phenolic carbon with a thickness of 1.5 mm for a fiber mass fraction of 42%. For the thermoplastic matrix, it consists of 12 layers of thermoplastic-PEKK carbon with a thickness of 1.9 mm for a mass fraction of 41% fiber.

3.0 Results and discussion

3.1 Effect of the thermocouple positions across the flame regime on the Temperature

Figure 2 and Figure 3 show how the average flame temperature of 35 thermocouples changes with equivalent ratio across both the vertical and horizontal directions. It can easily be seen that there is a very good linear relationship between the flame temperature and the position of flame away from the burner.

3.1.1 Vertical Position Result

For the vertically positioned 17 thermocouples, the linear relationship appears to be better than the horizontal set of thermocouples.

Figure 2 show how the flame temperature varies at different equal intervals in the vertical direction as the flame propagates out of the cone burner for different equivalent ratios. The temperature data used was measured by each thermocouple during the time of flame stability and the average peak value was calculated.

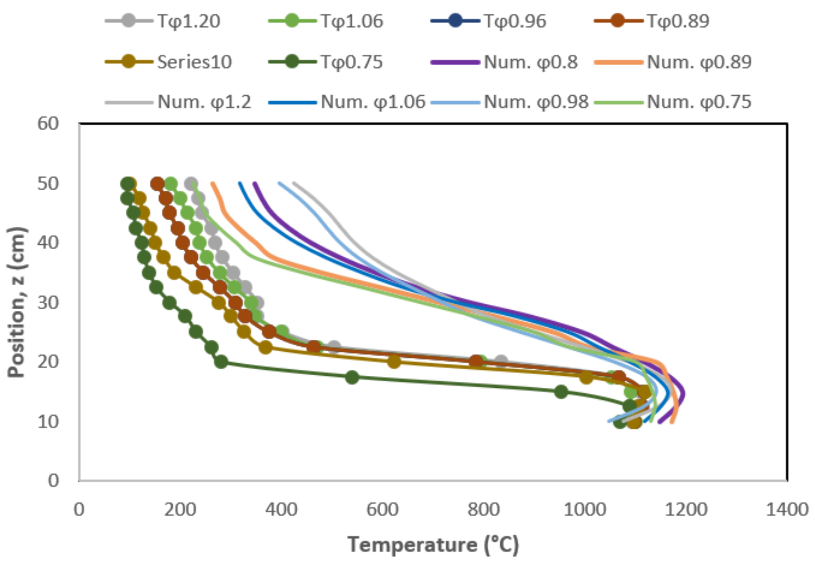

Figure 2. Effect of the vertical thermocouples from burner on the flame temperature

From the result, it can be seen that the flame temperature decreases with the position of the thermocouple. The positions having temperature values which agree with the FAA standard (1100 °C ±80 °C) are at 10 cm, 12.5 cm, 15 cm and 17.5 cm away from the burner, while the optimum temperature value of 1115.9 °C was recorded at the standard position of 10 cm.

In addition, the result of the FDS simulation was compared with the experiment, and it reveals the same trend of result that agrees with the experimental data. This shows that the code is a good solver for the fire test condition. However, the numerical models still requires modifications in order to obtain a closer agreement of results.

3.1.2 Horizontal position result

Figure 3 below shows the plot of the flame temperature as a function of the thermocouple temperature in the horizontal direction at different equivalent ratio.

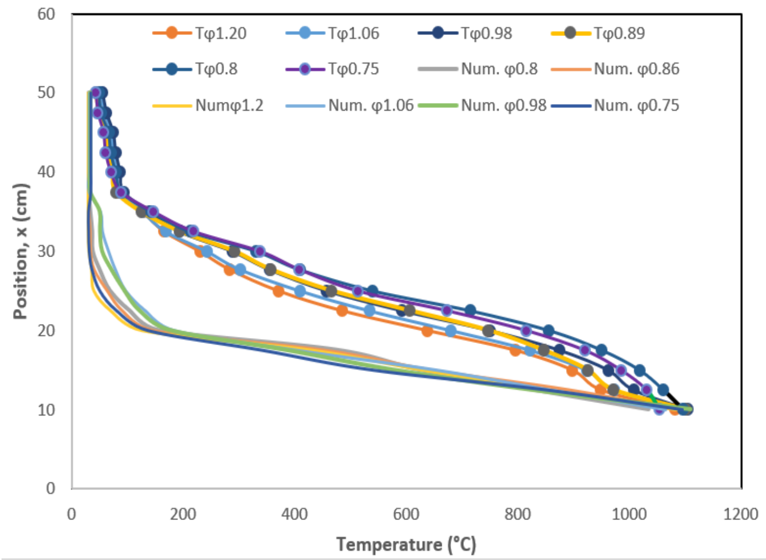

Figure 3. Effect of the horizontal thermocouples from burner on the flame temperature

In a similar trend, the flame temperature decreases with the position of the thermocouple. The positions having temperature values which agree with the FAA standard are at 10 cm, 12.5 cm and 15 cm away from the burner, while the optimum temperature value of 1101.5 °C was observed at a position of 10 cm. However, the results did not demonstrate a direct correlation between the position and equivalent ratio. Generally, the peak temperature of the vertical temperature is higher than the horizontal because of the phenomenon known as flickering i.e buoyancy effect which tends to cause the flame to propagate slightly in the vertical direction.

Also, flame stratification can be observed from the temperature results revealed in figure 2 and figure 3 i.e the regime of continuous flame (region of the highest temperature value), the intermittent regime and the plume regime (unburnt gas region which is mainly characterized by smoke and soot).

3.2 Effect of the equivalence ratio on heat flux and temperature evolution: Numerical and Experimental data

Simulations were carried out using the CFD code Fire Dynamics Simulator (FDS) version 6.7.0[6][8]. It solves the Navier-Stokes equations using an explicit finite difference scheme. As a CFD code, FDS models the thermally driven flow with an emphasis on smoke and heat transport. It is a large eddy simulation (LES) model using a uniform mesh and has parallel computing capability using Message- Passing Interface (MPI) [6]. Reactive flows are modelled using a turbulence model based on a LES approach, a combustion model based on the Eddy Dissipation Concept (EDC) and a thermal radiation model based on a gray gas model for the radiation absorption coefficient [6][9][10].

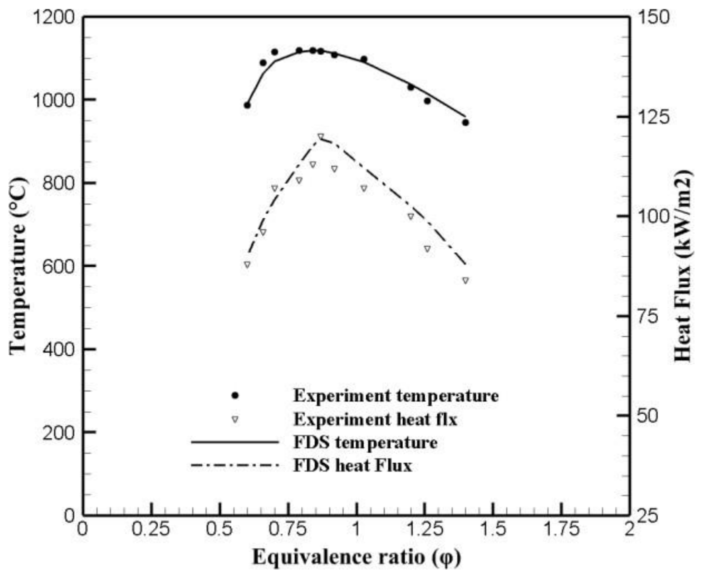

Fig 2. Evolution of heat flux and temperature as function of the equivalence ratio

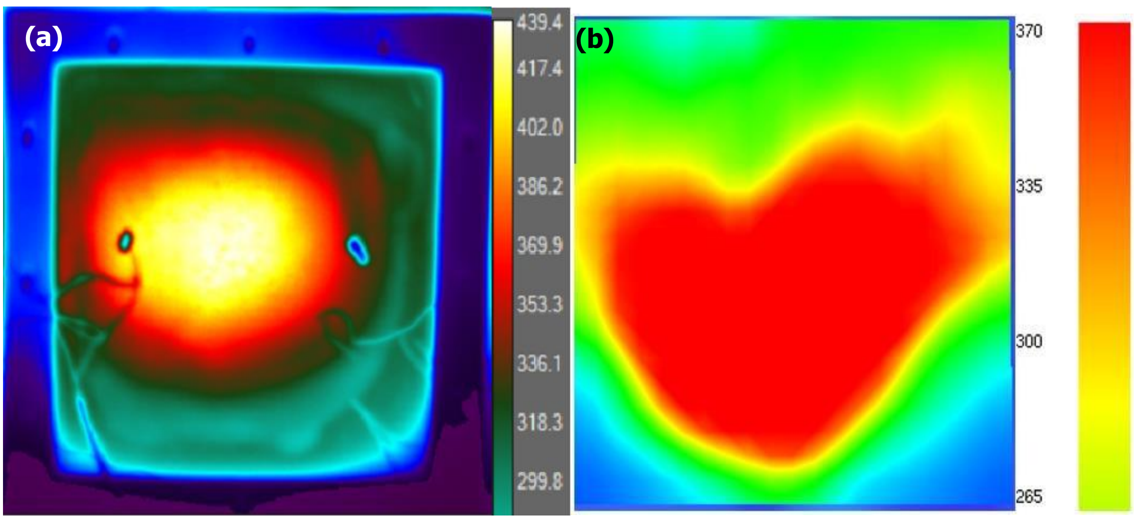

Fig 3. Experimental (a) and numerical (b) field temperature for a steel plate for the equivalence ratio about of 0.8.

3.3 Effect of the equivalence ratio on the thermal degradation of three composite materials.

For the effect of the equivalence ratio on the three composite materials, it is shown that the thermal degradation of these materials is obtained at the maximum for an equivalence ratio about of 0.8. In addition, it is also shown that the poorer the flame, the less the material thermally degrades and the more the flame is rich the more there is a build-up of soot on the surface of the sample. These observations were made by measuring the mass loss of the different sample. Moreover, at equivalence ratio of 0.8, better thermal stability of carbon-PEKK and carbon-BMI compared to carbon-phenolic was observed (cf. figure 4).

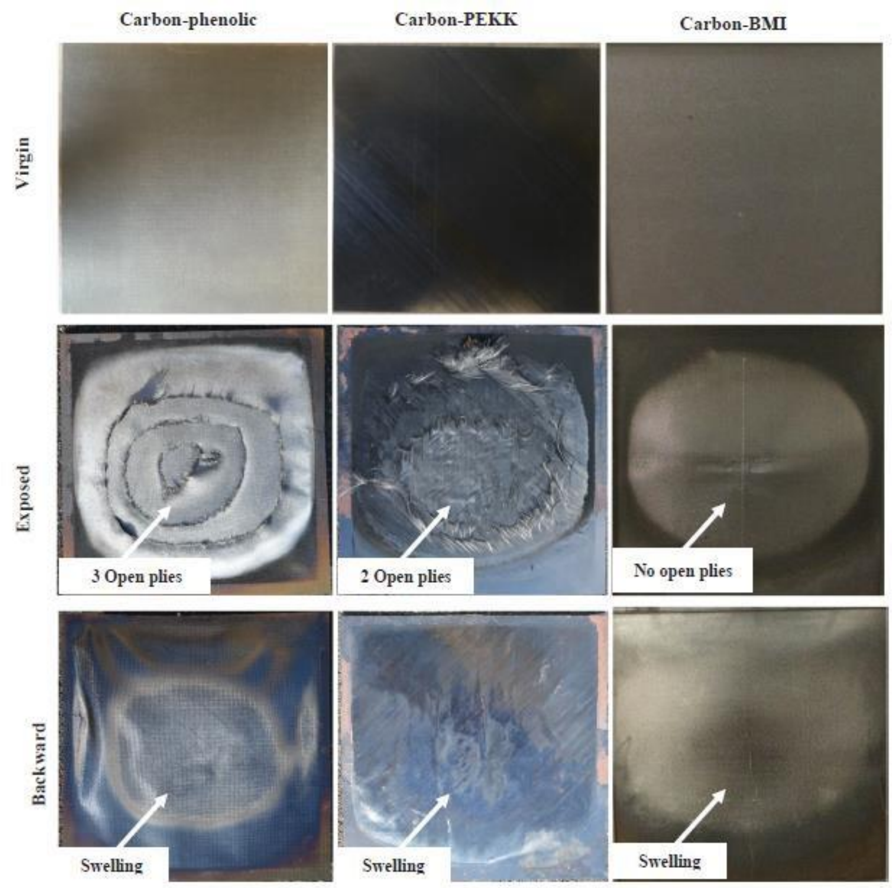

Fig 4. Photographs of the different composite samples before and after NexGen burner experiments at the equivalence ratio of 0.8.

4.0 Conclusion

In conclusion, the preliminary experiment revealed that the flame temperature varies with positions especially in the vertical direction and the flame is affected by the flickering effect (buoyancy). This therefore justifies the use of the optimum position of 10 cm away from the burner. The numerical and experimental work carried out in this study has shown that the equivalence ratio of a flame significantly impacts the temperature and flux field received on the wall of a material. In addition, a good agreement between the numerical and experimental results has been highlighted. This justified the ability of the CFD, FDS code to simulate an air / kerosene premix diffusion flame. From the results, it is found that the temperature and heat flux evolutions reach their maximum value for an equivalence ratio about of 0.8. Moreover, the fire behavior of composite materials strongly depends on the equivalence ratio of the flame. Indeed, for a poor or very rich flame, the flow rate of pyrolysis is small compared to that where the equivalence ratio is close to 1. Thus, by putting itself in the case of a capsule penetrating the atmosphere, it is possible to justify the difference of thermal degradation of the hulls of the system.

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