Heptane fires tests with forced ventilation

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HEPTANE FIRE TESTS WITH FORCED VENTILATION

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Abstract

This part of the EUREKA 499 program deals with fundamental experiments in the steady state obtained by both well defined fire sources and controlled ventilation conditions. A large number of sensors were used to describe the thermo-mechanic fields associated with these fires. These good quality results may be used for the future qualification of simulation tools.

Keyword

Heptane fires, steady states, temperature fields.

1 Introduction

Heptane fires used in EUREKA 499 were designed by France and Austria. They were managed by the French group, with an active participation from Austria.

One of the main objectives of France contribution in EU 499 program was the thermo-mechanic measurements related to well characterized fires. Compared to the initial program which was based on realistic vehicle fires, these specific experiments required some additional means:

- a control of air motion;
- a complete measurement field;
- a controlled fire source.

The air motion control was performed with a big fan (2.6 m diameter) installed by France. This ventilation unit allowed air flow velocities up to 3 m/s in the tunnel cross section. The accuracy of the control was about 0.1 m/s.

The basic measurement network installed by iBMB was reorganized and completed with the French instrumentation. In the final configuration, the German sensors were located in cross sections between -200 m and +100 m (relative to the fire). The French measurement system was set in the sections located between +100 m and +1500 m. An additional section was placed at -100 m. These sensors were similar to the

International Conference on Fires Tunnels, Böras, 10-11 octobre 1994, p. 36-50.

German ones, except for the smoke detectors (which do not provide quantitative absorption information) and a differential pressure measurement (giving coupled data concerning the hot layer thickness and its density).

In the previous experiments of the program, the performed fires did not present steady states of the heat releases, even for calibrated loads (wood cribs). A fundamental result of the French participation was obtaining steady state heat releases. The proposed fire source consisted of tubs filled with heptane with a remote controlled level.

One of the most important objectives of these experiments was the constitution of basic results allowing a comparison with all kinds of simulations.

2 The technical choices

The proposal to complement the final experimental program in the Reppar Fjord tunnel by adding some heptane fire tests in a pool configuration was clearly coming from a common wish to improve the scientific approach. Further, a heptane pool fire can be considered to be a close approximation to a real fire scenario occuring in a road tunnel, involving petrol combustion from one or several petrol tanks after a crash.

2.1 The scientific background

Pool burning has been studied extensively for many years at the laboratory scale or at large scale in the open air (i.e. in a free ventilated mode). Early work was undertaken in the 50s by the Russians Blinov and Khudiakov [1] and later reviewed by Hottel [2]. Complementary research was carried out later by Koseki and co-workers [3], Babrauskas [4] and an excellent review was written by Hall [5].

Thus a large amount of valuable information was considered available for future detailed interpretation of the results to be achieved with the EU 499 program.

2.2 Choice of the chemical

As regards the specific choice of heptane (see table 1 gathering some of the main characteristics of the product), a pure chemical, detailed reasons were reported previously [9].

n-Heptane main characteristics [6] [7] [8]	
Molecular weight	100.2 g
Flash point	-4° C
Freezing point	-90° C
Boiling point	98.4° C
Flammability limits (in air)	1.1% to 6.7%
Auto-ignition temperature	215°C
Density	0.68
Immediately Dangerous for life and Health	4250 ppm
$\Delta H°_L$ (gross) standard heat combustion (total)	48.07 MJ/kg
$\Delta H°_C$ (low) standard heat combustion (net)	44.56 MJ/kg

Table 1: Main characteristics of n-Heptane

Here too, relevant literature sources may help as a support in characterising the real experimental fires, chiefly inside or near the burning zone and the fire plume.

As an example, Yumoto and Koseki reported some detailed temperature measurements inside the reactive zone of rather large heptane pool fires [10] [11].

Some other works are useful to qualify heptane burning rates, air entrainment laws in the plume, soot production, combustion efficiency, total heat release rates and radiative fraction [11] [12] [13].

Indeed due to local constraints encountered in the Reppar Fjord tunnel, it was not possible to install all the instrumentation required for a comprehensive study of that kind.

Figure 1 illustrates one of those reference works.

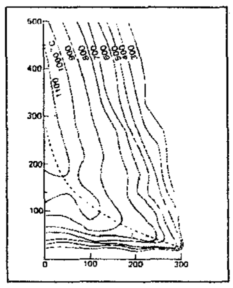


Figure 1: Temperature profile in a heptane flame [10]

2.3 Equipement design and features

An agreement has been found around the following basic ideas or technical necessities :

- fires should develop in the optically thick, radiative mode of burning (i.e. surface of the pan larger than $1 m^2$);
- fires should induce a significant heat release rate (several megawatts);
- steady-state, time controllable conditions had to be looked for (scientific purposes);
- the fire test procedure should be fully initiated and monitored at a fairly good distance (about 350 m far from the fire), without any direct possibility for the operators to witness the ignition process (safety concern).

In order to fulfil all these requirements and meet all safety aspects, INERIS proposed a technical solution comprising :

- steel circular pans of $1 m^2$, $2 m^2$ and $3 m^2$ with adequate ducts for the various connexions;
- a feeding line made of reheated coppertube, entirely sealed on site;
- a $2 m^3$ capacity heptane tank equipped with a level meter;
- two pneumatic pumps for heptane transfer through the feeding line;
- all other relevant instruments (thermocouples, transducers, valves ...) providing an easy way of monitoring the fire test in full safety. A simple regulation loop was used to keep the desired constant level of heptane in the pan [13].

The remote controlled ignition device had been designed by IBS engineers (Austria). Due to the intensive cold, it had been decided to ignite first a spongy material filled with a solvent, and located inside the heptane tub. This disposition proved to be highly efficient.

Figure 2 gives a schematic view of the operating system set in the Reppar Fjord tunnel.

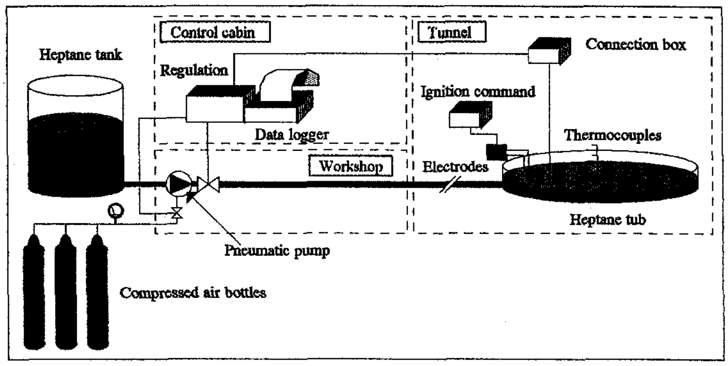


Figure 2: Experimental installation for heptane tub fires

3 INERIS preparatory test

3.1 Experimental set-up and procedure

The equipment necessary for these tests were first stored at INERIS. It was checked out in a realistic situation during a preliminary fire in the experimental gallery of INERIS (Figure 3). This test was carried out in September 1992, before the packaging of the equipement and its expedition to Reppar Fjord.

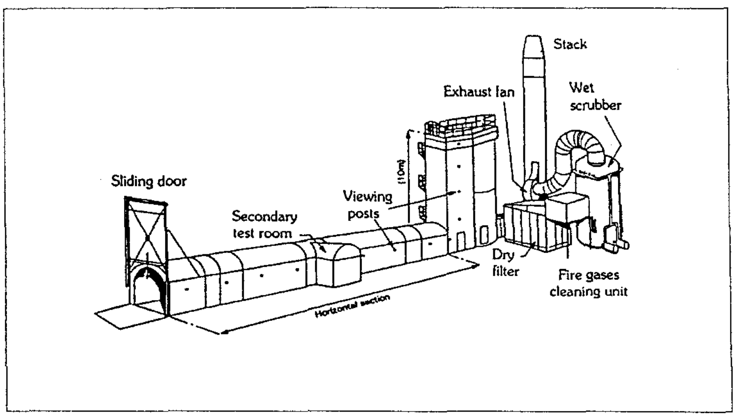


Figure 3: INERIS fire test gallery

This large scale fire testing facility has already been described elsewhere [14], [15], [16]. Notably it provides well controlled fire conditions.

Another result of this preliminary test has been to provide valuable information dealing with the heptane burning rate in physical conditions close to those expected in the Reppar Fjord tunnel.

3.2 Results and comments

Two drums of 200 l each of heptane were used. The overall test duration was just less than one hour.

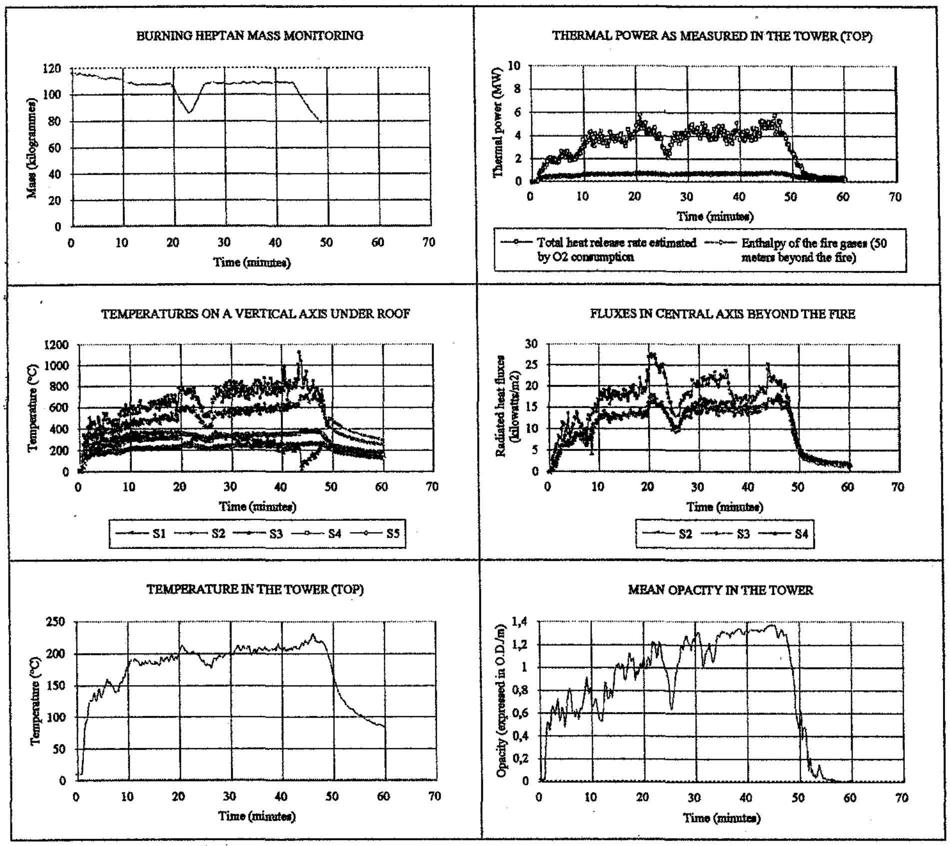


Figure 4: Main characteristics recorded during the 1 m² heptane test in the INERIS fire gallery (S1: cross section located 2.5 m downwind from the fire; S2: 5 m, S3: 10 m; S4: 20 m; S5: 40 m)

The reliability of the whole system proved to be quite satisfactory with the local conditions. Particularly, the regulation of the "constant level" revealed to be fairly accurate, since only a more or less 2 kg of heptane mass fluctuation was observed, once steady state conditions were reached (Figure 4). The gap in the middle of the diagram is the consequence of a manual change of a heptane drum.

From an estimation of the heptane consumption, one may calculate an average burning rate to be 100 g/s, which was rather higher than expected in the open air (65 to

75 g/s) (Babrauskas [4], Tewarson [17]). Significant re-radiation from the heated walls (refractory lined) of the gallery to the heptane pool could be a possible explanation.

Classical stratification of the fire gases along the gallery downstream from the pool was also observed (Figure 4). The total heat release rate averaged 4.0 to 4.5 MW in steady state conditions (Figure 4) showing a high overall combustion efficiency for a 1m² pool configuration.

Other complementary information about heat flux levels, opacity, chemical composition of the gases, temperature in the tower at the sampling port, (50 m far from the fire place) were also recorded (Figure 4).

4 Reppar Fjord tests

These tests were performed in severe conditions, during an unusual cold wave. The external temperature reached -20 °C. As a consequence, some incidents occurred during these experiments. They took a relative importance because these tests were calibrated. In these conditions, a small difference between the planned test and the performed experiment appears immediately in the results.

This obliged the French managers to modify the experiments considering the limited time available for these tests (less than one week) and the limited quantity of heptane stored. The initial proposed tests and the performed ones are indicated in table 2.

Test number	Planned test	Performed test	Date
1: H11	1 m²	1 m²	27 Oct. 92
2: H21	2 m²	1 m²	28 Oct. 92
3: H31	3 m²	3 m²	29 Oct. 92
4: H32		3 m²	29 Oct. 92

Table 2: Heptane tests program

Despite this unfavourable situation, the general results obtained are to be considered as positive.

Beyond the future modelling aspects, the influence of the ventilation conditions on the general organisation of the velocity and temperature fields was evaluated. The description of these physical boundary conditions is provided by a anemometer located upstream the fire. The instrument gave a local measurement of the air flow velocity. Thus it is only a simple indication of the ventilation intensity produced inside the tunnel by the fan.

For each experiment, one or two steady states were characterised. They largely depend on the equilibrium that exists between the thermal source and the ventilation conditions. Particularly, two incidents that occurred during experiments H11 and H21 showed the great importance of the stability of the fire source in this equilibrium .

Generally, each experiment has shown at least one steady state (Figure 5). This situation may require about 20 min to be established. The criterion of stationary state is the temperature recorded downstream from the fire.

Figure 5: Heptane tub fire in Reppar Fjord tunnel

4.1 Test H11

The tub surface is 1m². The initial operations were repeated for each experiment. Most of them are directly linked to safety aspects. They were:

- ventilation is established along the tunnel;
- the tub is filled with heptane through the feeding line;
- when the level of liquid is correct (regulation level), the pump is stopped;
- the tub is covered with a plastic film (this is necessary to avoid diffusion of explosive vapors);
- operators leave the fire location;
- at t = 0, the ignition is performed with the remote controlled ignition system;
- the plastic film burns and the fire develops slowly.

The longitudinal ventilation is controlled with the big fan located at the entrance portal of the tunnel. The velocity is fixed at 0.5 m/s during the first hour of the experiment. As a consequence, this test led to a clearly stabilised situation.

The incident that occurred about 30 min after ignition was the projection of concrete blocks due to the vaporisation of water contained in the ground lining.

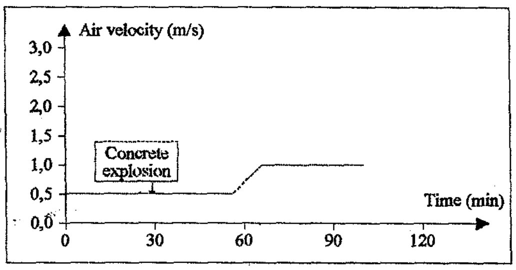


Figure 6: Ventilation conditions for heptane test H11

Some visual observations were made inside the tunnel during the test. They only dealt with that part of the tunnel where the access was possible in acceptable safety conditions, that means, upstream from the fire.

The backlayering phenomenon began as soon as the complete cross section was filled with smoke. After 20 min, a situation that appeared to be steady was established. The backlayering limit was stabilised at -150 m but it has been observed that this situation was linked to the ceiling roughness (Figure 7).

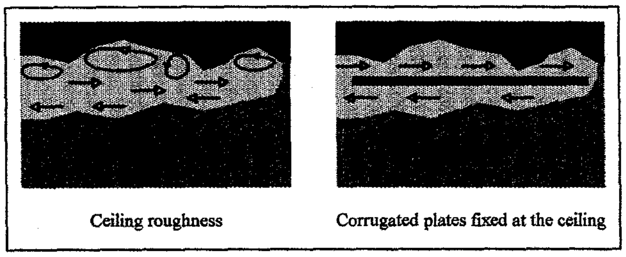


Figure 7: Influence of ceiling configuration on backlayering limits

After the increase in ventilation (Figure 6), all the smoke was blown downstream of the fire. This motion does not look like a conflict between cold and hot air masses. The observations show that the fumes are progressively diluted by fresh air. The visibility is restaured slowly.

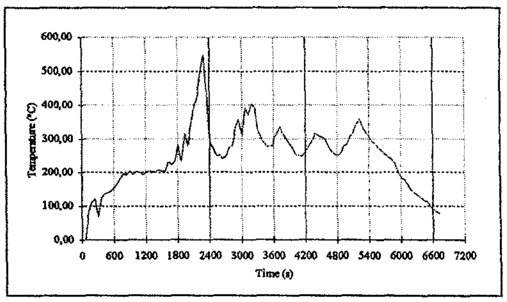


Figure 8: Temperature at the ceiling, above the fire

The incident that occured about 30 min after the ignition appears clearly in the temperature evolution (Figure 8). The equilibrium which resulted from the balance between ventilation and transient characteristics of the fire required first about 12 min to be locally established. Between this moment and 27 min, the steady state was slowly reached: in the fire area, the other parameters do not present any significant evolution.

About 27 min after ignition, a chaotic behaviour appeared. This is the consequence of the loss of control of the fire due to the concrete projections. However, a cyclic evolution was found (the period is 10 min for the four last cycles). This may be explained by the following evolution:

- the concrete projections create an overflooding of heptane out of the tub (pieces of concrete falling inside the tub);
- the increase of burning surface induces temperature peaks and protects also the concrete from direct radiations (this energy is used for the vaporisation of heptane);
- the concrete temperature decreases and, as a consequence, concrete projections stop;
- when all the heptane on the ground is burnt, the air temperature decreases and tends to reach the steady state level (asymptotic evolution);
- the concrete of the ground is exposed to radiations and new explosions happen, so that the cycle may begin again.

In the following tests the ground lining was insulated from the radiation in the fire area. The rockwool was installed on the floor, downstream from the tub. It is to be noted that this device did not prevent "concrete explosions" in other tests (particularly in the 3 m² tub fires). These "explosions" were located beyond the lining limits so that the fire was no longer disturbed.

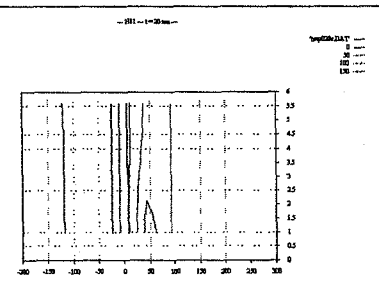
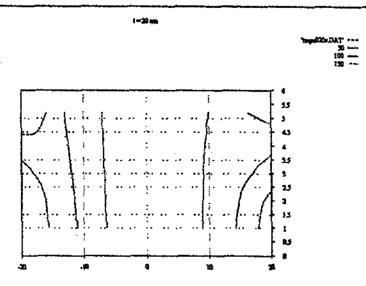
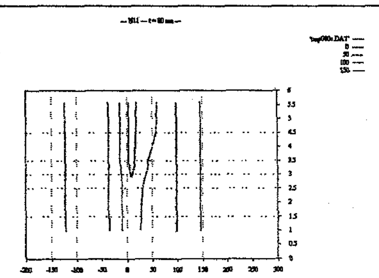
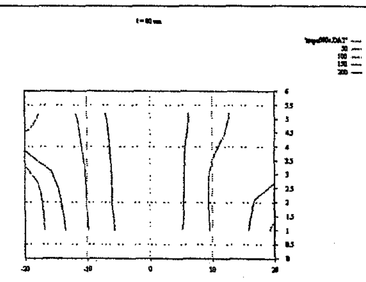
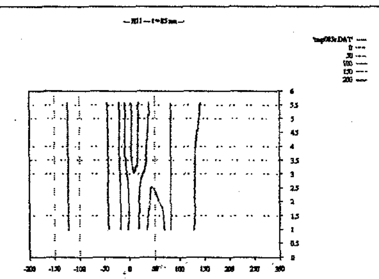
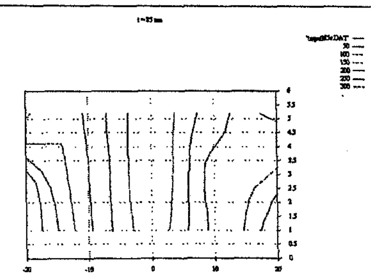
Time	"-200 m - +300 m" field	"-20 m - +20 m" field
20 min		
80 min		
85 min		

Figure 9: Temperature fields for steady state and chaotic states

Some temperature field evaluations (at various times) are presented in figure 9. A large width field (with regards to the distance parameter) is selected to show the evolution of temperature in the far field. In addition, a shorter width field is presented to allow comparisons in the fire area. Discrepancies seem to appear in the location of some isothermal curves between the two modes of representation. This is simply due to the principle of the software used to construct temperature fields in a 3D mode from the actual measurments. Nonetheless, valuable results have already been achieved by this procedure.

If the steady state corresponds to the situation described by the fields at t = 20 min, the chaotic behaviour provides a mean increase of temperature levels (see also figure 8), and the cyclic evolution of the fire induces cyclic expansions of energy. The situations described in figure 9 show the thermal fields during the last heat wave (t = 80 min corresponds to the minimum heat spread, and t = 85 min to the maximum). At this moment, the air velocity is higher than at t = 20 min (about 1 m/s).

4.2 Test H21

In this test, the size of the tub was kept equal to 1 m². The initial air velocity was increased, in comparaison to the H11 test. Two different steady states were obtained. They correspond to longitudinal velocities of 1.5 m/s and 2.0 m/s.

The incident that occured was the deformation of one of the metallic beams that supported the tub, so that burning heptane spread on the ground, increasing the fire power. In the next tests, this structure was reinforced.

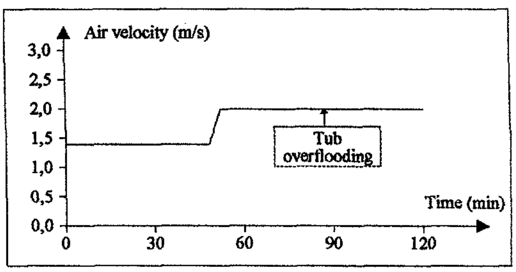


Figure 10: Ventilation conditions for heptane test H21

The increase in the ventilation was performed about 50 min after ignition. At this moment, the thermal field was not completely stabilised (Figure 11, section 0 m). This increase of air velocity induced a heat dilution effect downstream from the fire, so that the temperature generally decreased (Figure 11 section +10 m). On the contrary, the increase in the ventilation led to local increases near the fire of about 10°C (section 0 m).

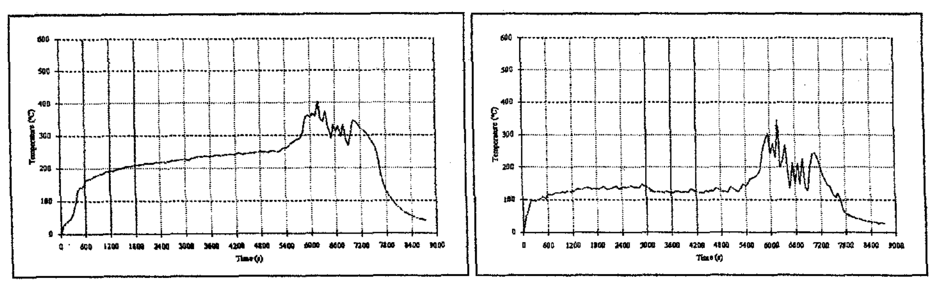


Figure 11: Temperatures recorded at the ceiling above the fire and 10 m downstream from the fire

In the two tests using a 1 m² tub, the heptane burning rate was about 80 $g.s^{-1}.m^{-2}$ determined from the level of the fuel in the storage tank (Figure 2).

4.3 Test H31

This test was performed with a 3 m² tub. An apparent stationary state was noted 20 min after ignition. At this moment, it was difficult to precise whether this observation corresponded to a real steady state because the fire power began to decrease slowly. The H32 test eventually showed that the asymptotic situation had actually been reached in this experiment.

The backlayering developed up to 80 m upstream from the fire (visual observations, figure 12). Some of the mechanisms leading to this state are described in figure 7.

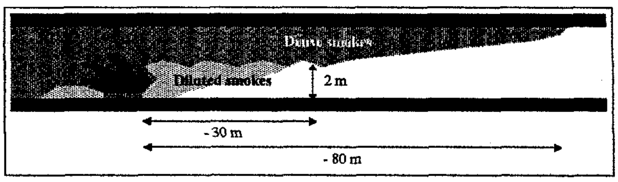


Figure 12: Observed situation of test H31

The very low temperature conditions of heptane storage outside the tunnel (about -20°C) explained that a control valve failure occurred, cutting off the heptane feed to the tub. From this moment, the fire power output decreased slowly to final extinction.

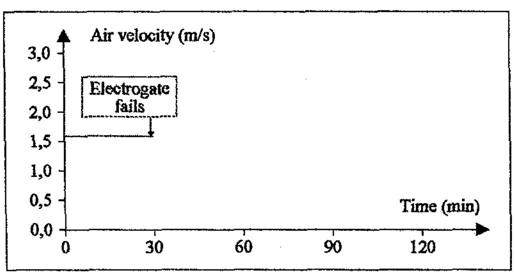


Figure 13: Ventilation conditions for heptane test H31

4.4 Test H32

This fourth test was not planned in the initial program. Experiment H32 could be performed because the failure that happened during H31 test was rapidly located and repaired. This second fire was ignited about three hours after the first one. This test was performed without any incident.

The initial conditions were identical to the H31 test. Particularly, air velocity was maintained at 1.5 m/s. The development of physical conditions inside the tunnel was identical to H31 test. This demonstrates a remarkable reproducibility of phenomena relative to fires in tunnels.

About 40 min after ignition, the ventilation was increased to 3.0 m/s. This operation took 10 min (Figure 14).

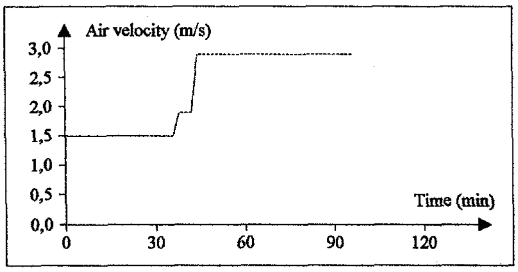


Figure 14: Ventilation conditions for heptane test H32

Under the longitudinal wind effect, flames were bended. Their development reached about 5 meters (Figure 15). Buoyancy effects were observed downstream from the fire.

Figure 15: Picture of the 3 m² heptane tub

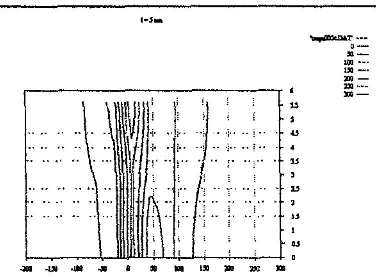
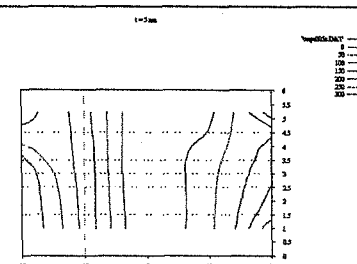
Time	"-200 m - +300 m" field	"-20 m - +20 m" field
5 min		

Figure 16: Temperature fields at t = 5 min in the central vertical plane

A short study shows that the thermal convective effects are fully developed in the fire zone. This situation appears clearly in the very first minutes of the fire. In the central vertical plane, the buoyancy effects induce a massive motion of air toward the ceiling (Figure 16). The impact zone of the plume is located about 8 m downstream from the fire. This is the place where the wall temperature was maintained at a high level during the experiment. A the end of the test, when the fire is extinguished, a big amount of heat comes from this zone (thermal restitution effects).

In the lateral vertical planes, the maximum of temperature is located at the ceiling, between 8 m and 10 m. This is coherent with the observation dealing with the central plane. The isothermal curves show that, in these lateral planes, heat convection happens from this point down to the ground where a new relative temperature maximum is found between 16 m and 18 m.

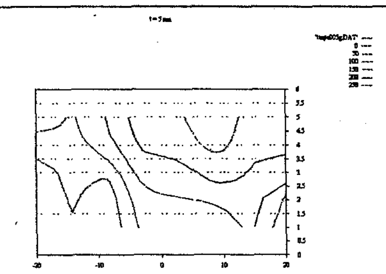
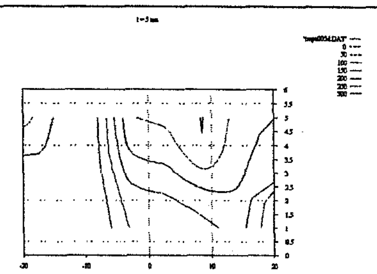
Time	Left side (east)	Right side (west)
5 min		

Figure 17: Temperature fields at t = 5 min in the lateral vertical planes

This situation suggests that two large symmetrical eddies of opposite rotation are responsible for heat convection downstream from the fire (Figure 18). They are the result of the interaction between natural convection (Benard eddies) and the forced convection due to controlled ventilation.

The development of these flow structures is linked to the fact that the fire does not represent any material blockage in the tunnel cross section like previous fires (rail vehicles may have important blockage coefficient, larger than 60%). The motions in relation with buoyancy effect may be fully developed (Figure 18).

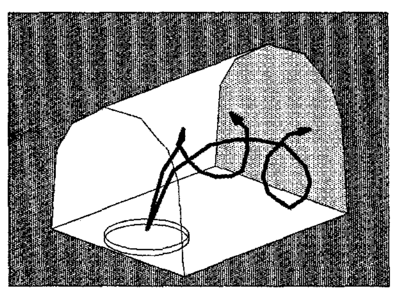


Figure 18 : Scheme of the eddies linked to buoyancy effects downstream from the fire zone

The representation of the cross section thermal field downstream from the fire shows that the development of the eddies is actually not symmetrical (Figure 19). The right eddy convects more energy than the left one. This induces a dissymmetry of the temperature levels.

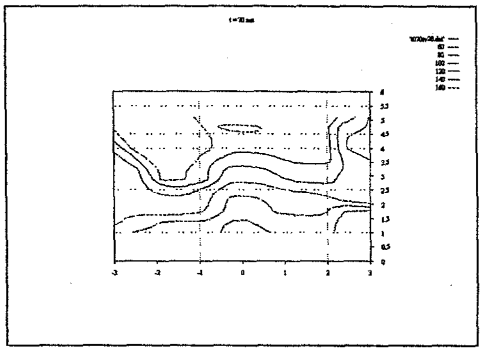


Figure 19 : Temperature fields in the vertical cross section 20 m downstream from the fire at t = 70 min

In regions located far downstream from the fire, the motion looses its three dimensional character. Velocities measured in the central vertical plane show great movements of air coming backward to the fire. These situations are quite classical in this kind of experiment and they are linked to the importance of buoyancy effects.

In the two tests using a 3 m^2 tub, the measured heptane burning rate is in order of 75 $g.s^{-1}.m^{-2}$. This value is in agreement with Babrauskas [4] and Tewarson [17] estimations.

5 Conclusions

The heptane fire experiments performed by France with the active participation of Austria in EUREKA 499 encountered some incidents. However, the tests are to be considered successfull for the following reasons:

- each experiment has been characterized by at least one steady state;
- a great amount of data were collected during these tests;
- their quality is compatible with a future comparison with simulation works;
- two tests proved a remarkable reproducibility of the phenomena, giving more credibility to simulation processes.

Some phenomenological descriptions presented in this paper show that the analysis drawn from these experiments may provide valuable information. The qualitative content of this information may be considered as an excellent basis to a technical orientation for modelling purposes.

Finally, it is important to state that numerous other available data have not been presented in this analysis.

Aknowledgements

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