On the effect of gas mixture non-homogeneity and pre-ignition turbulence on gas explosions in high density congested industrial facilities

by

Kees van Wingerden
Brian Wilkins
and
Geir Pedersen

Christian Michelsen Research
Bergen, Norway

Abstract

The consequences of vapour cloud explosions are dependent on many factors, such as gas cloud size, fuel reactivity, ignition location, degree of congestion and degree of confinement. In case of a realistic release there are, however, two additional factors that affect the outcome of an explosion, viz. turbulence generated by the release itself or by wind and the non-homogeneity of the gas cloud.

An experimental study has been performed to investigate these two aspects of gas explosions. The tests to investigate the effect of pre-ignition turbulence were performed in a 50 m^3 representation of a process facility provided with some obstructions representing larger process equipment and partial confinement. The turbulence was generated by a jet release. To vary the degree of turbulence three different flow rates were used. Both the gas in the process facility and the gas involved in the release are premixed, homogeneous and flammable. In this way only the effect of the turbulence generated by the release is studied. The turbulence intensity in the mixture before ignition, and flame speeds and generated pressures after ignition are measured.

The tests to investigate the effect of gas cloud non-homogeneity were performed in a highly congested representation of the process facility mentioned above (50 m^3). The gas clouds were generated from a jet release of pure gas in the initially gas free facility. Gas concentrations were measured continuously at various locations in the facility. Ignition was effected after generated turbulence by the jet was dissipated. Flame speeds and overpressures were measured during these tests. Tests with homogeneous stoichiometric clouds were carried out as reference cases.

1. INTRODUCTION

In spite of considerable efforts in order to avoid gas releases and ignition sources there is still a remaining risk of gas explosions in petro-chemical installations including offshore rigs. Gas releases are occurring on a regular basis and sometimes such releases are ignited as well [1]. Ignition may lead to fire and/or explosion and may have serious consequences as witnessed by more recent events such [2, 3].

Regarding the risks, investigations are being carried out to understand the factors influencing the course of dispersion, fire and explosion. In the field of gas explosions, research has been going for almost 20 years at Christian Michelsen Research in Norway. Experiments were carried out at several scales in several geometries to understand the processes occurring during gas explosions [4-7] and to allow for validation of the 3-D CFD model FLACS (FLame ACceleration Simulator) which has been developed for prediction of the course and effects of gas explosions in congested environments [8,9].

Recently full-scale explosion experiments performed in process facilities representing offshore modules with dimensions of 8m x 8m x 25.6m and 12m x 8 m x 28m demonstrated the potential of gas explosions [10]. The magnitude of the pressures obtained during these explosion tests is such that only very expensive structural measures can avoid escalation and prevent fatalities. It must be emphasised, however, that the full-scale explosion experiments were carried out using worst case initial conditions. The highest pressure was obtained when ignition was effected at the edge of a homogeneous stoichiometric gas cloud filling the entire rig. In all tests reported in [10] homogeneous gas clouds were used.

In reality the occurrence of a homogeneously mixed stoichiometric cloud filling the entire facility is unlikely. It therefore appears unnecessary to design process facilities in such away that they can withstand the high explosion overpressures that may occur in case of worst case position ignition of a stoichiometric cloud filling the entire facility. Information is, however, needed to quantify the potential of non-homogeneously mixed clouds emerging from a realistic release. Turbulence generated by the release itself may in fact cause an increase of flame speeds initially possibly resulting in an overall increase of the overpressures generated.

In this light experiments were carried out in medium-scale representations of process facilities which are presented in the present document. The experiments concern the effect of initial turbulence generated by realistic releases and explosions in non-homogeneous gas clouds. In these investigation the ignition location was varied as an accident parameter.

2. EXPERIMENTAL RIG

All experiments presented below were performed in a model of an offshore compressor module. The vessel is 8.0 m long, and has both a height and width of 2.5 m. The module contains a deck plate positioned 1.25 m above the floor. During the experiments to investigate the effect of initial turbulence generated by jet releases this deck plate was solid with grated areas. In the experiments to study non-homogeneous gas clouds the deck was fully grated. In the rig there are several obstacles representing the main equipment in the compressor module such as the compressors themselves and two control rooms at the deck plate (See Figure 1). In the experiments to study non-homogeneous gas clouds more equipment was added including a few pipe-racks and a cable-rack (See Figure 2). The internal volume is 50 m^3. The roof, floor and the two long sides of the module are solid. The short ends of the facility are available for venting.

The gas mixtures were prepared using a recirculation system. The system consists of 8-inch piping, a centrifugal fan and two sets of butterfly valves that allow for isolation of the system from the vessel prior to ignition. Flammable gas can be added to the recirculated flow until the desired gas concentration is reached, controlled by an infrared analyser. Plastic sheeting that was clamped around the edges of all vent areas retains the gas mixture. This plastic was not removed prior to ignition.

The ignition source consisted of a single electric spark.

The diagnostics consisted mainly of piezoelectric pressure transducers mounted within the module at six locations, and video recordings for flame speed measurements.

3 RESULTS AND DISCUSSION

The results of the experiments are presented and discussed for each of the two test series. When necessary additional information is given on the details of the experiments.

3.1 Effect of initial turbulence

A typical accident situation that may lead to the build-up of flammable gas clouds in a petro-chemical installation is a release occurring from a high pressure vessel or pipe containing flammable material. The release itself is a source of pre-ignition turbulence. This turbulence may in case of ignition of the cloud enhance the strength of the explosion. Another source of pre-ignition turbulence may be wind. The present investigation considers the effects of pre-ignition turbulence generated by both jet releases and wind separately.

Jet release

Experiments were run with pre-ignition turbulence with jet flows from an arrangement consisting of 4 lances (inner diameter 22 mm) directed towards a common point (distance between lance outlet and common point 35 cm). The jet pipes and associated frame are illustrated in Figure 3. The jet pipes were located at the centre of the upper deck. Three different turbulence levels have been tested defined by different lance flow rates: no flow, medium flow rate (U_{lance} = 29 m/s) and high flow rate (U_{lance} = 54 m/s). It is emphasised that homogeneous mixtures were used in both the facility and the jets, i.e. only the effect of pre-ignition turbulence is studied. The effect of gas cloud inhomogeneities occurring during a real release of pure gas from equipment was not considered here.

The turbulence field for the medium flow rate case was characterised using pulsed hot wire anemometry. At the point where the jets emerging from the lances collide, turbulence velocities of 1.7 m/s to 2.8 m/s were measured (depending on the direction) decreasing when the distance to the common point increased.

Ignition was in most experiments effected at the centre of the upper deck (UD-C) what coincides with the common point of the jets emerging from the lances. In some tests ignition was effected in the centre of the lower deck (LD-C). The experiments reported here were performed using methane.

The results are presented in Table 1.

Table 1 Effect of initial turbulence generated by a jet release

Test no.	Lance mode	Ignition position	Maximum overpressure (bar)
13-16	off	UD-C	0.217
15-18	medium	UD-C	0.322
14-17	high	UD-C	0.378
20	off	LD-C	0.422
22	medium	LD-C	0.432
21	high	LD-C	0.467

UD-C = upper deck centre
LD-C = lower deck centre

As Table 1 shows the investigated levels of pre-ignition turbulence appears to be especially important when it affects the initial stages of flame propagation, i.e. when present around the ignition source. Increasing the turbulence intensity resulted in an increase of the flame speed during the initial stages of flame propagation and because of that a considerable increase of the overall pressure in the module.

Ignition at the lower deck results in considerably higher pressure for all situations than the upper deck ignition cases but probably due to relatively low level of turbulence generated by the lances in comparison to the turbulence generated by the combustion itself at the grating in the deck. This turbulence “overshadows” the pre-ignition turbulence completely. As a result the effect of turbulence in the lower deck ignition cases cannot be distinguished.

Wind

To investigate whether wind generated turbulence can have an effect on gas explosions in congested environments an experiment was performed where the gas-air mixture was recirculated through the facility using a fan (See Figure 4). The fan caused a volumetric flow of 1.2 m^3/s through the upper deck region and a flow of 1.4 m^3/s through the lower deck area. The wind speed in the facility was approximately 0.4 m/s. Turbulence measurements were not performed. Figure 4 shows that two hoods had to be fabricated to connect the module to the recirculation system. These hoods are made out of plastic sheeting and failed during the explosions. The wind was entering the module from the northern end.

Ignition was effected in the centre of the upper deck and at the north end of the module also at the upper deck (upwind end). Table 2 shows the results compared to experiments where the fan was shut off. In all cases the transition hoods were present.

Table 2 Effect of initial turbulence generated by an external fan (representing wind generated turbulence)

Test no.	Fan mode	Ignition position	Maximum overpressure (bar)
12	off	UD-C	0.213

9	on	UD-C	0.269
11	off	UD-N	0.249
10	on	UD-N	0.223

UD-C = upper deck centre
UD-N = upper deck north

The results show a 25 % increase of the pressure when ignition is effected in the centre of the facility. This is slightly beyond the reproducibility of the experiments and therefore representing an effect. Ignition at the northern end of the module does not lead to any overpressure increase. This may partly due to translation (transport) of the flame into the module reducing the total length of flame propagation in the southern direction resulting in a reduction of the overpressure. Wind generated turbulence will partially compensate for this effect.

3.2 Non-homogeneous gas clouds

The tests performed to investigate the consequences of non-homogeneous gas clouds were performed in a higher congested version of the facility in which the tests to investigate the effects of pre-ignition turbulence were studied. Moreover it should be stressed that the deck was fully grated instead of partially grated. The geometry is a 1:3.2 downscaled replica of the 8 m wide rig used in [10].

In contradiction to the tests in which the effects of pre-ignition turbulence was studied there was no gas in the facility before the start of an experiment. The flammable gas (methane) was stored in a 0.24 m^3 reservoir. The initial pressure in the reservoir was 20 bar. The reservoir was connected to the facility via a 4.5 m long ¾’’ diameter flexible hose. A pneumatically operated, fast-acting, large-bore valve completed the gas release system. Two release rates were applied: the first of the two was obtained by allowing the gas to flow through the hose unrestricted; the second was obtained by restricting the outflow using a pipe cap through which a 5 mm hole had been drilled. The releases occurred under no wind conditions. The plastic sheeting was not removed so that the gas accumulated in the facility. The valve was normally closed during an experiment when the pressure in the reservoir was fallen to approximately 3 bar. The total amount of gas that is released into the facility would give rise to a stoichiometric mixture in case of a fully homogeneously mixing.
In case of the ¾’’ opening the release time was 10-15 s. The 5 mm release lasted two minutes.

Two release locations were used: one location at the north-end of the facility at the lower deck and one at centre of the facility at the upper deck. The north end release occurred down into the facility. The central upper deck release occurred form one of the sidewalls across the facility. The release points have been indicated in Figure 1.

Gas concentrations were measured continuously during the release at 8 locations in the facility. The gas sensors were based on a newly available gas-sensitive semiconductor gas-sensing device. Five sensors were placed in the upper deck volume approximately midway between the grated deck and the roof. The other three remaining sensors were located similarly in the lower deck area.

Results are presented in Table 3. Results are given for a release from a 5mm nozzle from the north end of the module (test 16) and for a release from a ¾'' hole from the centre (test 17). In these tests ignition was effected in the centre of the rig at the upper deck just above the grated deck. Ignition was effected after a certain period to allow for turbulence generated by the release to die out. In the table the test results are compared to the results of tests using homogeneous gas clouds as a reference.

Table 3 Results of tests performed with non-homogeneous clouds compared to the results of tests with homogeneous gas clouds (ignition UD-C).

Test no.	Gas leak location	Hole size (mm)	Gas conc'n range (% v/v)	Max. pressure (bar)
16	North-LD	5	5.9-8.1	0.365
17	Centre-UD	19	6.5-10.2	0.473
Reference test	NA	NA	9.5	0.45

The results of the gas concentration measurements in the two release tests show that the gas cloud in the facility is relatively homogeneous throughout the entire test showing that both jet releases are sufficiently strong to cause good mixing. The most homogeneous mixture is obtained for the high release rate although the range of gas concentrations as measured during the test seems to indicate differently. The higher homogeneity agrees with the larger release rate being a better mixer. The low release rate is on average in the order of 0.025 kg/s whereas the high release rate is in the order of 0.25 kg/s.

The fact that the vent openings of the facility were closed during these tests will support the gas cloud build-up. In reality wind would, especially in the low release rate situation, have diluted the gas cloud in the facility.

The pressures obtained in the high release case and in the tests with premixed homogeneous stoichiometric clouds are very similar whereas the test with the low release rate resulted in somewhat lower pressures. The latter observation is in agreement with the somewhat lower concentrations measured during the low release rate test. The lower concentrations in this test may be a result of leakages from the rig to the outside through small openings especially in the plastic sheeting.

It should be mentioned that in case of an explosion the expansion flow arising from the expanding combustion products will cause an additional mixing of the unburned gas ahead of the flame during the explosion.

4 CONCLUSIONS

Experiments have been performed in a medium-scale version of a petro-chemical installation to investigate the influence of factors related to the gas cloud build-up phase, viz. pre-ignition turbulence caused by wind and jet releases and non-homogeneity of the gas cloud.

The tests showed that pre-ignition turbulence due to a release or even wind may lead to an increase of the explosion overpressure. The effect of initial turbulence due to a jet release is only strong when ignition occurs in the turbulent jet and increases with the release rate. In case of ignition outside the area affected by the turbulent jet the effect of the turbulence in congested installations is limited. The effect of pre-ignition turbulence arising from wind is modest but may be stronger if higher wind speeds are used than used in the present investigation.

Jet releases (low and high rate releases) can lead to the build-up of relatively homogeneous gas clouds especially in enclosed congested volumes. In case the total amount of gas that is released is close to that of a stoichiometric cloud filling the entire volume of a congested enclosure the explosion pressures in case of ignition can be close to that of a homogeneous stoichiometric cloud.

5 ACKNOWLEDGEMENT

The authors of this article greatly acknowledge the support given by BP, Conoco, Elf, Esso, Gasunie, Gaz de France, Mobil, Norsk Hydro, Statoil, HSE, NPD, Phillips, BMFT and the Commission of the European Communities.

6 REFERENCES

[1] Offshore Accident and Incident Statistics Report 1994, Offshore Technology Report - OTO 95 953, Health and Safety Executive, May 1995

[2] The Hon. Lord Cullen (1990), *The Public Inquiry into the Piper Alpha Disaster*, Department of Energy, UK, CM 1310, HMSO, London

[3] Lewis, D.J. (1989), *Soviet blast – the worst yet?*, Hazardous Cargo Bulletin, August 1989, pp. 59-60

[4] Hjertager, B.H., Bjørkhaug, M. and Fuhre, K. (1988), *Gas explosion experiments in 1:33 and 1:5 scale offshore separator and compressor modules using stoichiometric homogeneous fuel/air clouds*, J.Loss Prev. Process Ind., vol.1, pp.197-205

[5] Hjertager, B.H., Bjørkhaug, M. and Fuhre, K. (1988), *Explosion propagation of non-homogeneous methane-air clouds inside an obstructed 50 m^3 vented vessel, J.Haz.Mat.*, vol. 19, pp. 139-153

[6] Hjertager, B.H., Fuhre, K. and Bjørkhaug, M. (1988), *Concentration effects on flame acceleration by obstacles in large-scale methane-air and propane-air vented explosions*, Combust. Sci. and Tech., vol. 62, pp. 239-256

[7] Van Wingerden, K., Pedersen, G.H. and Wilkins, B.A. (1994), Turbulent flame propagation in gas mixtures, Hazards XII, European Advances in Process Safety, pp. 249-261, IChemE Symposium Series No. 134

[8] Bjerketvedt, D., Bakke, J.R. and Van Wingerden, K. (1993), *Gas Explosion Handbook, Version 1.2*, Christian Michelsen Research report no. CMR-93-A25034

[9] Van Wingerden, K., Storvik, I., Arntzen, B., Teigland, R., Bakke, J.R., Sand, I.O. and Sørheim, H.-R. (1993), *FLACS-93 - A New Explosion Simulator*,

Paper presented at the 2nd International Conference and Exhibition "Offshore Structural Design Against Extreme Loads, ERA Report 93-0843

[10] The Steel Construction Institute (SCI) (1996) *JIP BFETS Phase II, Interim Technical Information Release*, 7th May 1996

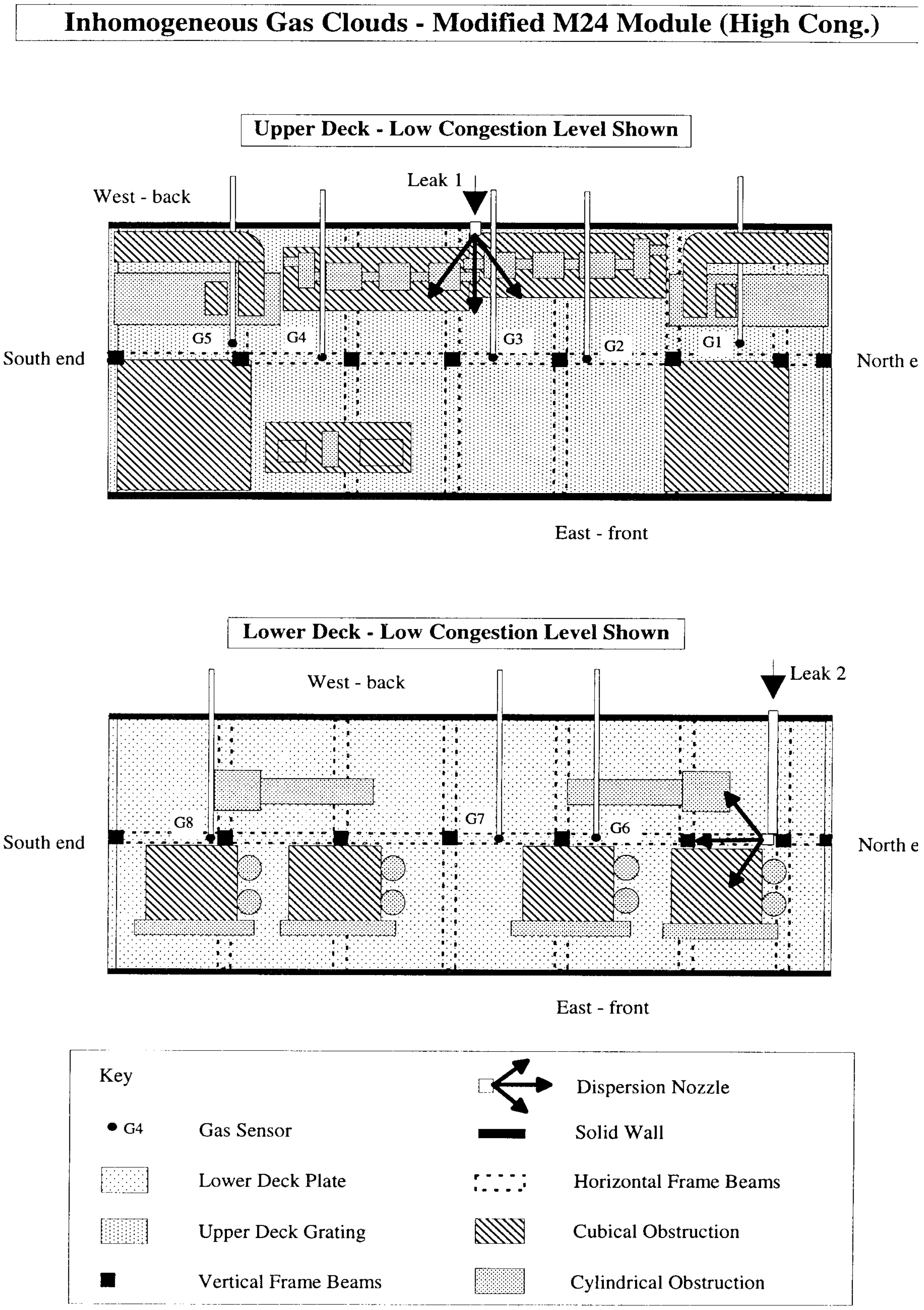

Figure 1 Schematic view of main equipment items inside 50 m^3 process facility.

Figure 2 End view of facility used during experiments to study explosions in non-homogeneous gas clouds.

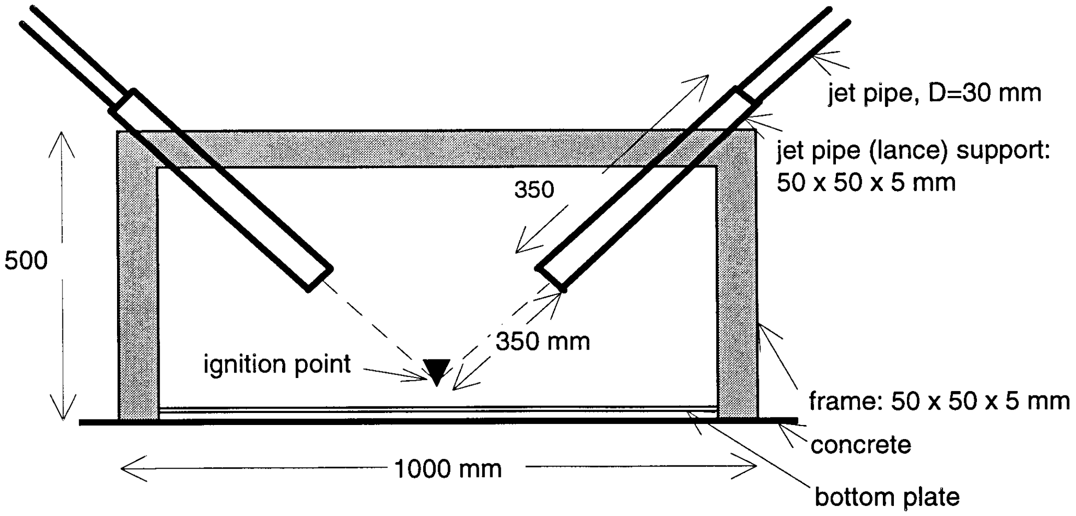

Figure 3 Lance configuration used to investigate the effect of initial turbulence on flame propagation in a 1:5 scale representation of an offshore module.

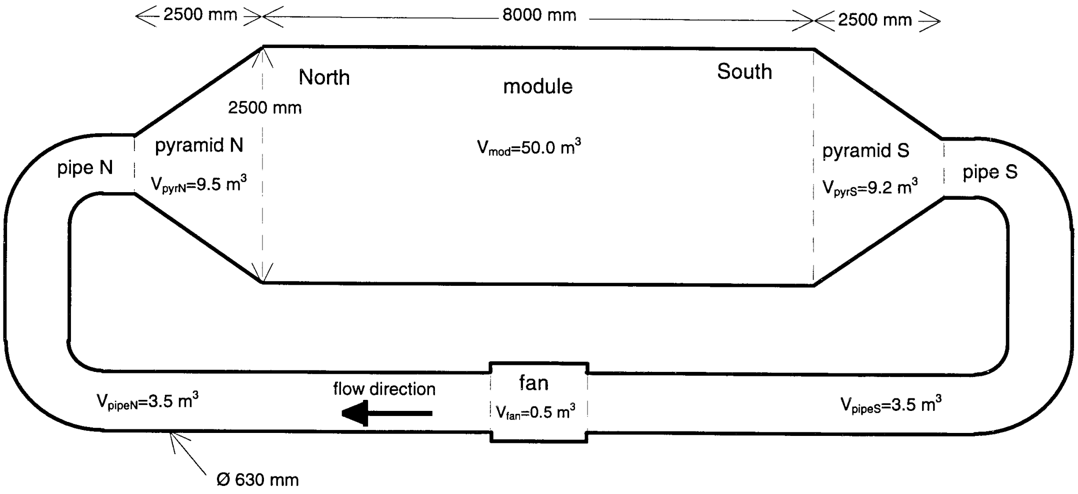

Figure 4 Experimental set-up to investigate the influence of wind generated turbulence on flame propagation.