Forschungszentrum Karlsruhe

in der Helmholtz-Gemeinschaft

Wissenschaftliche Berichte

FZKA 6811

Measurements of Flammability and Flame Acceleration Limits at Low Pressures

M. Kuznetsov*, V. Alekseev*, I. Matsukov*, W. Breitung, S. Dorofeev

Institut für Kern- und Energietechnik
Programm Kernfusion

*R&D Company NIS-VARGOS, St. Petersburgh, Russia

Report on EFDA Subtask TW2-TSS-SEA5.4

Forschungszentrum Karlsruhe GmbH, Karlsruhe
2003

Impressum der Print-Ausgabe:

Als Manuskript gedruckt

Forschungszentrum Karlsruhe GmbH
Postfach 3640, 76021 Karlsruhe

Mitglied der Hermann von Helmholtz-Gemeinschaft
Deutscher Forschungszentren (HGF)

ISSN 0947-8620

MEASUREMENTS OF FLAMMABILITY AND FLAME ACCELERATION LIMITS AT LOW PRESSURES

Abstract

Results of an experimental study on limits for strong Flame Acceleration (FA) as a function of initial pressure are presented. The range of initial conditions studied covers the range of conditions typical for VVPSS ex-vessel LOCA scenarios. The experimental data give a basis for extension of FA σ–criterion to the range of sub-atmospheric pressures typical for ITER accident scenarios.

MESSUNG VON BRENNBARKEITS- UND FLAMMENBESCHLEUNIGUNGSGRENZEN BEI KLEINEN DRÜCKEN

Zusammenfassung

Die Ergebnisse einer experimentellen Studie über die Abhängigkeit der Grenzen einer starken Flammbeschleunigung (FA) vom Anfangsdruck werden präsentiert. Die Spannweite der dabei gewählten Anfangsbedingungen deckt den Bereich der typischen VVPSS Ex-Vessel LOCA-Szenarien ab. Die neuen experimentellen Daten stellen eine Basis zur Erweiterung des σ–Kriteriums für Flammbeschleunigung in einem Bereich von Unterdrücken dar, die für Unfallszenarien im ITER typisch sind.

Contents

Introduction

Three-dimensional gas distribution calculations for the ITER-VV, the connected SP and the PSS have shown that in ex-vessel LOCA scenarios explosive hydrogen-air mixtures can exist in the VVPSS over many hours. Loads that can be expected from various combustion events in flammable hydrogen mixture depend essentially on the combustion regime. Three typical combustion regimes can be distinguished in gaseous mixtures. These include slow subsonic deflagrations, fast supersonic flames, and detonations. During 2002, detonation potential was studied on the basis of detonation cell sizes calculations (task TW2-TSS-SEA3.5). To study the limiting conditions for slow and fast flames an experimental work was initiated on measurements of flammability and flame acceleration limits at ITER typical initial conditions. All together the analysis of flammability, flame acceleration (FA) limits and detonation limits should provide a basis for determination of possible combustion modes expected in various LOCA scenarios in the VVPSS. This in its turn will give a possibility to design the measures necessary to remove the risk of fast hydrogen combustion modes by steam dilution or full inertization of the VVPSS atmosphere.

Background

The effect of initial temperature on flame acceleration for hydrogen-air and hydrogen-air-steam mixtures has been investigated in obstructed channels by SNL, BNL, KI [1-4]. The combined effect of initial temperature and pressure on the regime of turbulent flames propagation in obstructed areas was studied by SNL for hydrogen-air-steam mixtures [2]. Most part of data presented in [1-4] have been obtained for a temperature of 110ºC and for pressures of 1 and 3 bar.

In the present work, all the tests have been carried out under the temperature of 110ºC to compare the results with data available from previous tests [1-4]. Initial pressures was chosen to be 0.1 and 0.5 bar (as ITER-typical pressures) and of 1 and 3 bars to compare with data of [1-4].

Using the expansion ratio σ as a potential of effective flame acceleration [5] allows estimating flame acceleration limits for initial conditions for tests being done in this work. It follows from Figs. 1-2 that the critical expansion ratio decreases with temperature increase and with pressure decrease. For example, the critical expansion ratio is in the range from 2.8 to 3 for temperature 383K and for pressure 1 atm. Critical expansion ratio for elevated pressure 3 atm is in the range from 3.2 to 3.4.

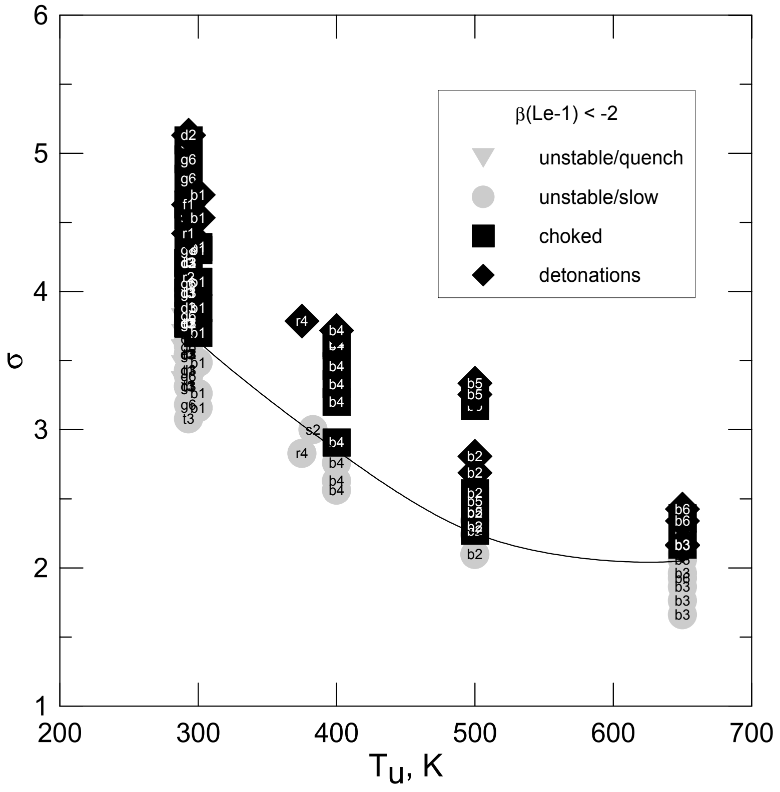

Figure 1. Resulting combustion regime as a function of expansion ratio σ and initial temperature T_u for hydrogen-air-steam mixtures. Black points - fast and gray points - slow combustion regimes [5].

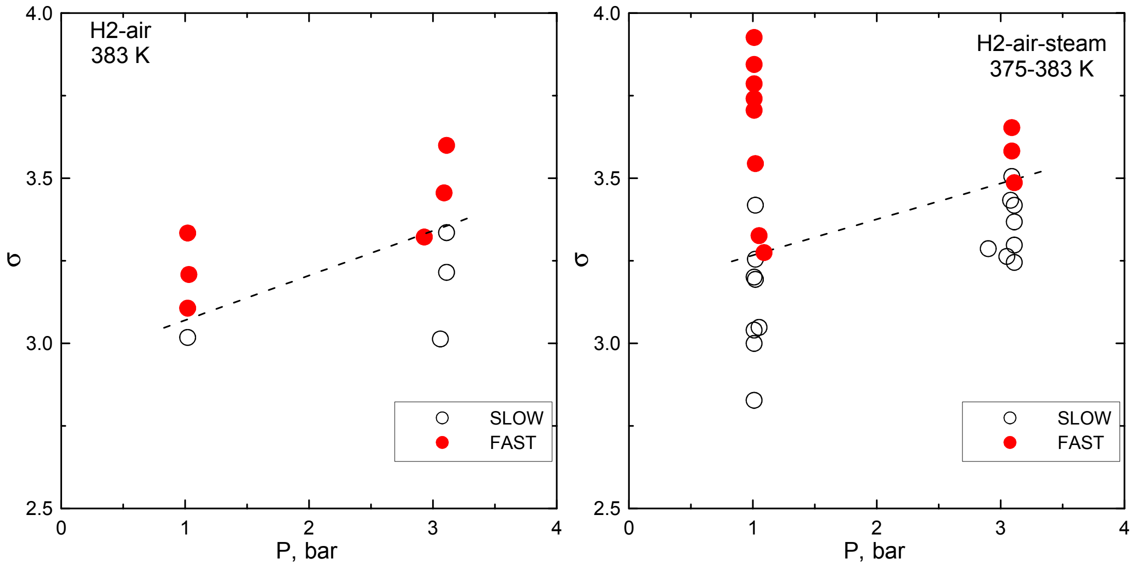

Figure 2. Dependence of expansion ratio σ versus initial pressure.

Test definition

As it was shown in [6], three basic points are enough to construct analytical description of flammability limits in triple system hydrogen-air-steam: Lower Flammability Limit (LFL), Upper Flammability Limit (UFL) and maximum steam concentration of a flammable stoichiometric hydrogen-air mixture with steam. Similar to flammability limits, three key points could be distinguished as basic points for construction of Flame Acceleration (FA) domain (see Fig. 3):

1. Lower Flame Acceleration Limit (LFAL) – a minimum hydrogen concentration, at which flame accelerates effectively ($[H_2O] = 0$);
2. Upper Flame Acceleration Limit (UFAL) – a maximum hydrogen concentration, at which flame accelerates effectively ($[H_2O] = 0$);
3. Maximum Steam Concentration (MSC) – a maximum steam concentration for stoichiometric hydrogen-air mixture, at which flame accelerates effectively ($\phi = 1$).

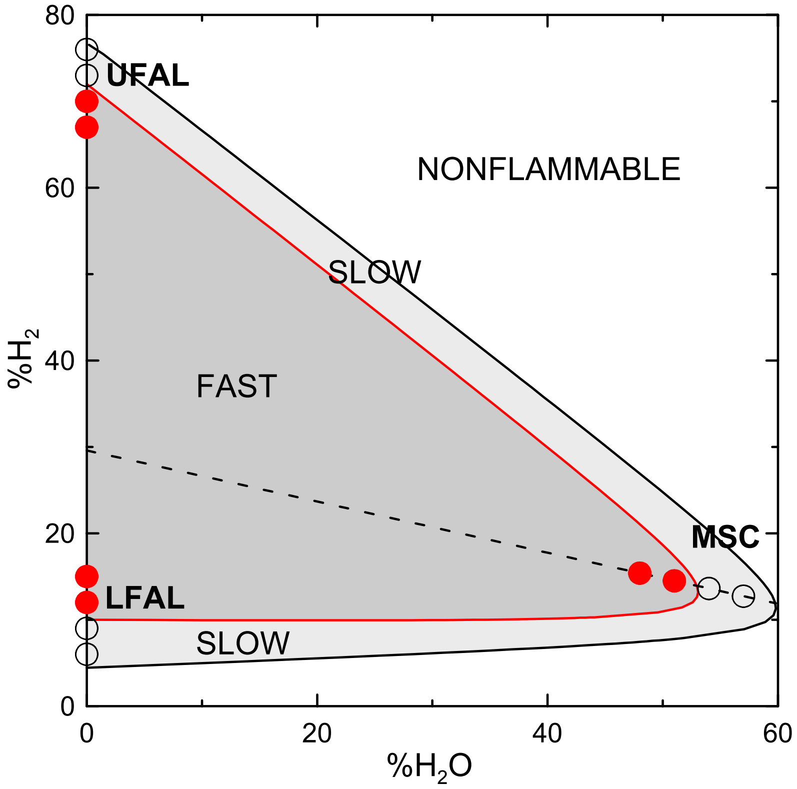

Figure 3. Combustion regimes diagram (illustrates test matrix definition).

The test mixtures chosen for the definition critical points definition are presented in Table 1.

Table 1. Test matrix (initial temperature 383K).

	Pressure, bar				
	0.1[*)]	0.5	1	3	
LFAL	8-11%H_2	8-11%H_2	9-12%H_2	10-13%H_2	16 tests
UFAL	73-76%H_2	72-75%H_2	71-74%H_2	70-73%H_2	16 tests
MSC (ϕ=1)	54-60%H_2O	54-60%H_2O	52-58%H_2O	49.5%H_2O[**)]	16 tests

[*)] scale effect is expected at pressure 0.1 bar due to small values of L/δ ($L/\delta < 100$) [5].

[**)] concentration corresponds to steam saturation at 383K and P=3 bar [6].

Experimental details

The FA experiments at temperature 110C and pressures from 0.1 to 3 bar were carried out in the Vargos Heated Tube (VHT). A heated detonation tube of 121 mm id and 8-m-long was used in the tests. The tube was manufactured of a stainless steel pipe of 6 mm wall thickness and consisted of two 4 m sections. Blockage ratio (BR) of obstacles spaced by diameter was equal to 0.6 in the tests. Instrumentation ports were located at regular interval of 0.48 m. A scheme of the test facility is shown in Fig. 4. Hydrogen-air mixtures with different steam content have been used as test mixtures. Hydrogen concentration was changed in dry mixtures from 9-11%H2 to 74-80%H2 in air. In damp mixtures steam content was changed from 46%H2O to 52%H2O with stoichiometric H2-air (ϕ = 1). The ignition of mixtures was made by means of a spark plug. Taking into account huge difference of tested mixture sensitivity, energy of electric spark was varied in several order of magnitude (from less than 1 J to 1 kJ). The heating system consisted of 18 units (including 16 controlled by synthetic diamond sensors): 8 elements of 0.5 kW power provided heating of tube wall; 2 elements of 0.25 kW power were used for heating of tube ends; 6 elements (2 x 1 kW for walls and 4 x 0.25 kW for flanges) were used for heating of two mixing tanks; and 2 elements of 0.25 kW power were for steam generator and connecting tubes. Heating system of the tube supported temperature uniformity 110 ± 1C. All the connecting pipes and faucets have been overheated to prevent steam condensation.

The steam generator charged with water distillate allowed to produce above 5 bar of steam.

The test mixture preparation procedure included the next steps:

1. Preparing dry mixture at the ambient temperature in advance. The desired test gas composition was achieved using the precise method of partial pressures.
2. Producing steam at test temperature by heating a required amount of water in the separate pre-evacuated volume.
3. Heating dry test mixture to the test temperature.
4. Final preparing test gas composition by injecting hot dry mixture into the tank with steam. The gas was then diffused for a period of time to ensure uniform mixing.

Measuring system consisted of 16 collimated germanium photo-diodes FD-9 and FD-10, 6 pressure transducers (piezoelectric transducers PCB-H113A and piezoresistive transducers D2.5) to record pressure and light signals during combustion processes. Final pressure in the tube after the combustion was measured using piezoresistive pressure gauges and manometer. All the pressure gauges both piezoelectric and piezoresistive were calibrated. One of piezo-resistive pressure gauges was used to prepare mixtures in heated tanks. A calibration characteristic of piezo-resistive pressure gauge mounted in heated tank is plotted in Fig. 5. This calibration was made at working temperatures into the mixing tank 110-130C.

Additionally thermal gauges have been placed axially inside the tube and near from internal surface of the tube to get data on test mixture and tube wall temperature vs. time. A typical curve of mixture heating into the tube is presented in Fig. 6. Characteristic time of the thermal equilibrium between heating elements and tube with mixture was above 1 hour. Tube was heated starting of initial temperature 25ºC.

Data acquisition system was based on four 12-bit ADC controllers installed in IBM PCs (L-1250 type, up to 500 kHz sampling rate).

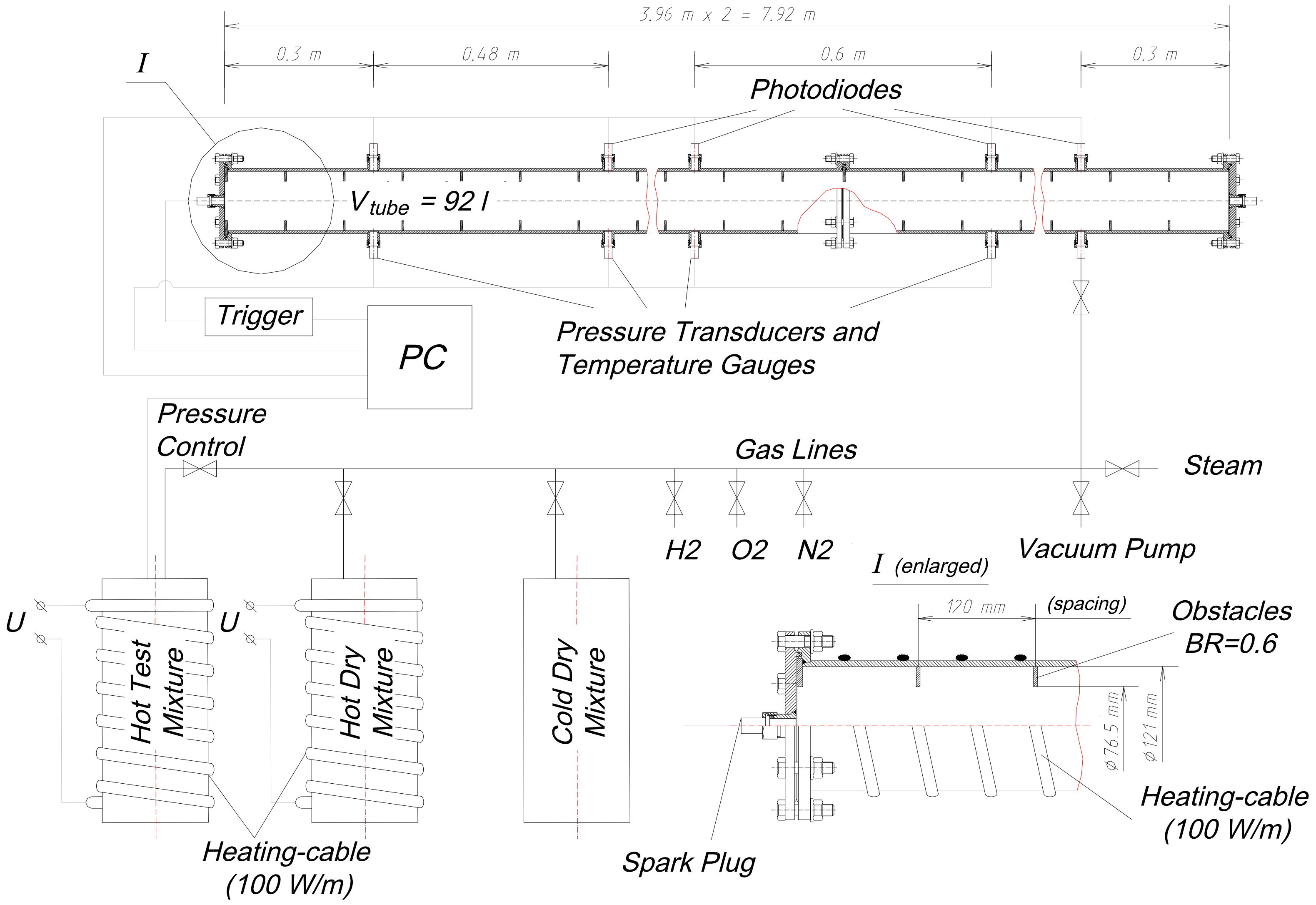

Fig. 4. Scheme of the test facility.

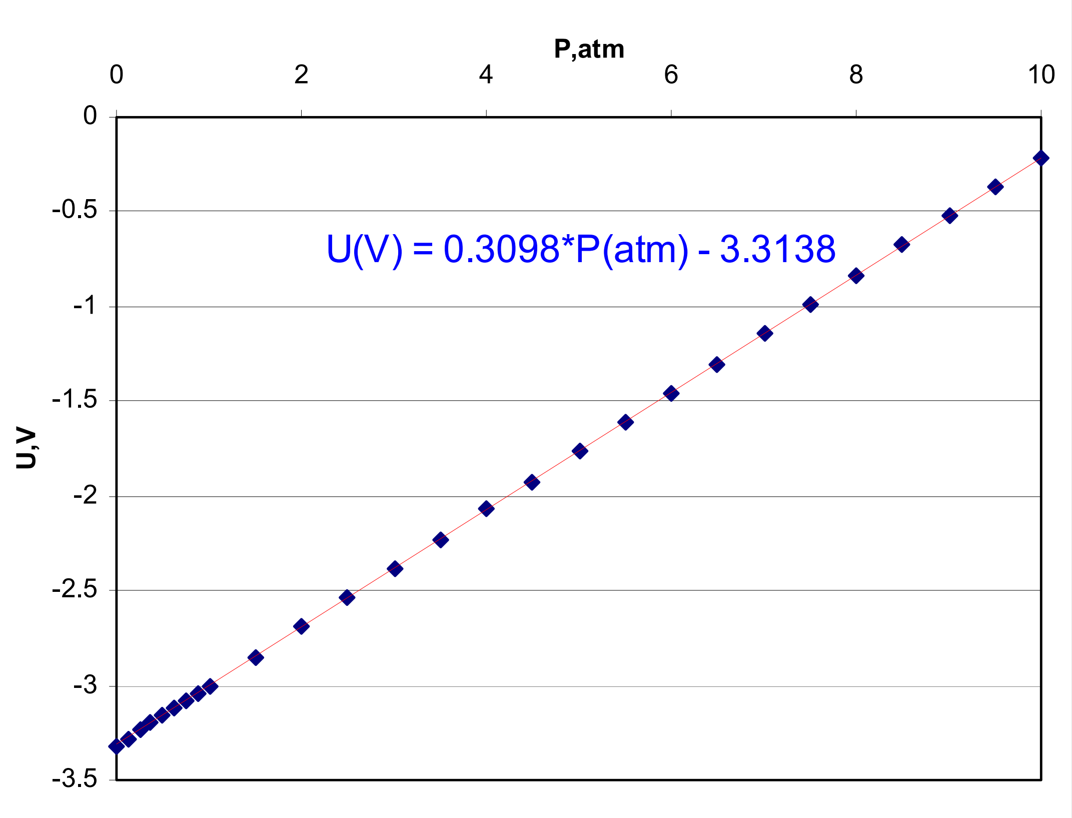

Fig. 5. Calibration characteristic of piezo-resistive pressure gauge.

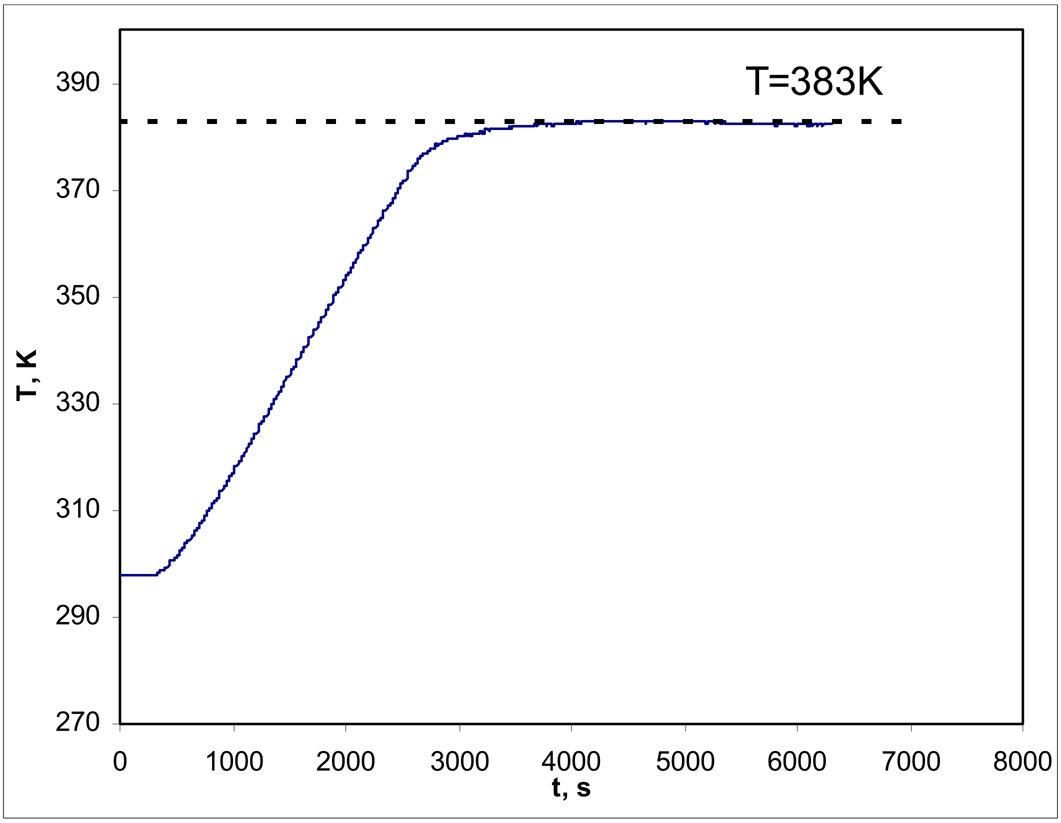

Fig. 6. Dynamics of the tube with mixture heating.

Experimental results

Initial conditions of tested mixtures and main preliminary test results are presented in Tables 2 and 3.

Table 2: Initial conditions and test results for dry H2-air mixtures

##	%H2	T,K	σ	P, atm	Mode
ht004	9	383	2.73	0.2	2
ht003				0.5	2
ht006				1	2
ht046				3	2
ht051	9.5	383	2.82	0.2	1
ht050				0.5	2
ht048				1	2
ht047				3	2
ht018	10	383	2.91	0.2	3
ht016				0.5	3
ht015				1	3
ht014				3	2
ht010	11	383	3.08	0.2	3
ht009				0.5	3
ht008				1	3
ht007				3	3
ht032	74	383	3.15	0.1	3
ht031				0.2	3
ht029				0.5	3
ht028				1	3
ht027				3	3
ht041	75	383	3.08	0.1	2
ht040				0.2	3
ht039				0.5	3
ht038				1	3
ht037				3	3
ht025	76	383	3.01	0.1	2
ht022				0.2	3
ht021				0.5	3
ht020				1	3
ht019				3	1
ht036	78	383	2.85	0.1	1
ht034				0.2	2
ht033				0.5	3
ht052				1	3
ht045	79	383	2.78	0.1	1
ht044				0.2	1
ht043				0.5	2
ht042				1	1
ht056	80	383	2.70	0.1	1
ht055				0.2	1
ht054				0.5	1
ht053				1	1

Table 3: Initial conditions and test results for damp stoichiometric H2-air mixtures

##	%H2	%H2O	T,K	σ	P, atm	Mode
ht070	15.98	46	383	3.60	0.1	3
ht069			383	3.60	0.2	3
ht068			383	3.60	0.5	3
ht067			383	3.60	1	3
ht124			386	3.58	3*)	3
ht063	15.38	48	383	3.51	0.1	2
ht062			383	3.51	0.2	3
ht061			383	3.51	0.5	3
ht060			383	3.51	1	1
ht125			386	3.49	3*)	3
ht074	14.79	50	383	3.42	0.1	2
ht072			383	3.42	0.2	3
ht065			383	3.42	0.5	3
ht071			383	3.42	1	2
ht126			386	3.40	3*)	1
ht077	14.20	52	383	3.33	0.1	1
ht076			383	3.33	0.2	1
ht075			383	3.33	0.5	1
ht057			383	3.33	1	1

*) to prevent steam condensation at 3 atm test mixtures were overheated up to 386K.

Three typical flame propagation regimes have been distinguished preliminary in the tests (Tables 2-3): 1) slow quenched flame; 2) slow subsonic flame (v<cr - flame velocity was less than sonic velocity in reactants); 3) fast sonic flame (cr<v<cp - flame velocity was less than sonic velocity in products, but more than sonic velocity in reactants). Characteristic velocity was estimated as average velocity during steady-state phase of flame propagation. Critical points with slow-fast flame propagation regimes are presented in Table 4.

Table 4: Critical points of flame acceleration at different initial pressures.

P, atm	%H2	%H2O	T,K	σ	Mode
dry					
0.2	9.5	0	383	2.82	1
0.2	10	0	383	2.91	3
0.5	9.5	0	383	2.82	2
0.5	10	0	383	2.91	3
1.0	9.5	0	383	2.82	2
1.0	10	0	383	2.91	3
3.0	10	0	383	2.91	2
3.0	11	0	383	3.08	3
dry					
0.1	75	0	383	3.08	2
0.1	74	0	383	3.15	3
0.2	78	0	383	2.85	2
0.2	76	0	383	3.01	3
0.5	79	0	383	2.78	2
0.5	78	0	383	2.85	3
1.0	79	0	383	2.78	1
1.0	78	0	383	2.85	3
3.0	76	0	383	3.01	1
3.0	75	0	383	3.08	3
with steam					
0.1	15.38	48	383	3.51	2
0.1	15.98	46	383	3.60	3
0.2	14.20	52	383	3.33	1
0.2	14.79	50	383	3.42	3
0.5	14.20	52	383	3.33	1
0.5	14.79	50	383	3.42	3
1.0	15.38	48	383	3.51	1
1.0	15.98	46	383	3.60	3
3.0	14.79	50	386	3.40	1
3.0	15.38	48	386	3.49	3

Summary

We have presented results of an experimental study of limits for strong FA as a function of initial pressure. The range of initial conditions studied covers the range of conditions typical for VVPSS ex-vessel LOCA scenarios.

The experimental data give a basis for extension of FA σ–criterion to the range of sub-atmospheric pressures typical for ITER accident scenarios. The analysis work on the extension of σ–criterion has been started.

Acknowledgement

The authors acknowledge the technical review and suggestion of our colleague Dr. Jörg Starflinger.

References

1. Ciccarelly G., J. Boccio, T. Ginsberg, C. Finfrock, L. Gerlach, H. Tagava, and A. Malliakos. The Effect of Initial Temperature on Flame Acceleration and Deflagration-to-Detonation Transition Phenomenon. NUREG/CR-6509, BNL-NUREG-52515, 1998.
2. Sherman M., M. Berman, and R. Beyer. Experimental Investigation of Pressure and Blockage Effects on Combustion Limits in H_2-Air-Steam Mixtures. SAND 91-0252, 1993.
3. Dorofeev S., V. Sidorov, A. Dvoinishnikov, A. Denkevits, A. Efimenko, and A. Lelyakin. Large Scale Hydrogen-Air-Steam DDT Experiments in the RUT Facility. Test Series 1996. RRC KI 80-05/16, 1997.
4. Sherman M., S. Tieszen, and W. Benedick. The Effect of Obstacles and Transverse Venting on Flame Acceleration and Transition to Detonation for Hydrogen-Air Mixtures at Large Scale. NUREG/CR-5275, SAND 85-1264, 1989.
5. Dorofeev S. B., M. S. Kuznetsov, V. I. Alekseev, A. A. Efimenko, and W. Breitung. Evaluation of limits for effective flame acceleration in hydrogen mixtures. *J. Loss Prev. Proces. Ind.*, 14, 583 (2001).
6. Kuznetsov M., A. Lelyakin, and S. Dorofeev. Flammability limits for nuclear safety applications. Report RRC KI, 2000.