5 th International Seminar on

FIRE AND EXPLOSION HAZARDS

23rd-27th April 2007, Edinburgh, UK

CONTROL OF THE DEFLAGRATION-TO-DETONATION TRANSITION

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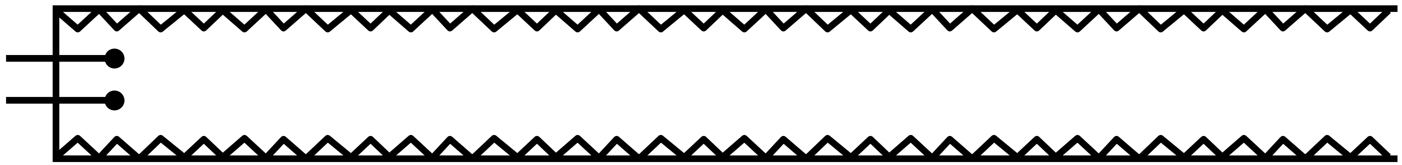
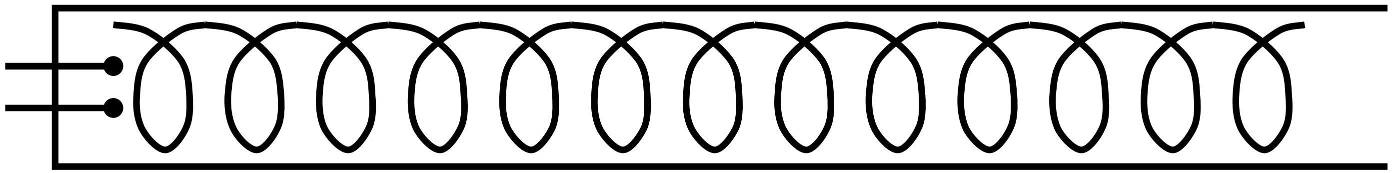
DRAG SYSTEMS

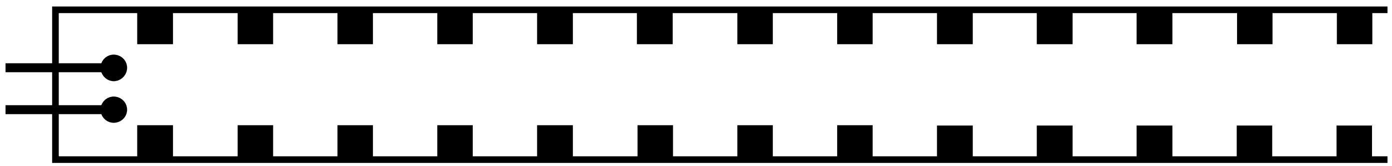
Rough tubes



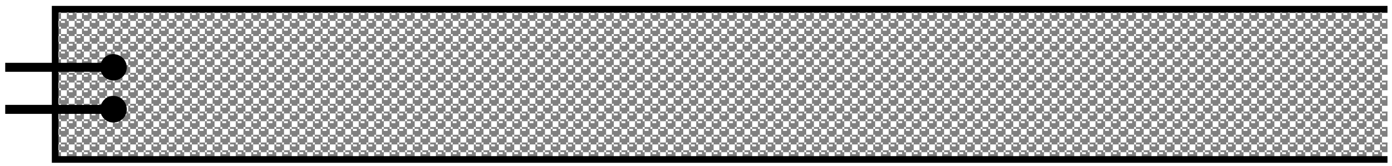
Schelkin "spiral"

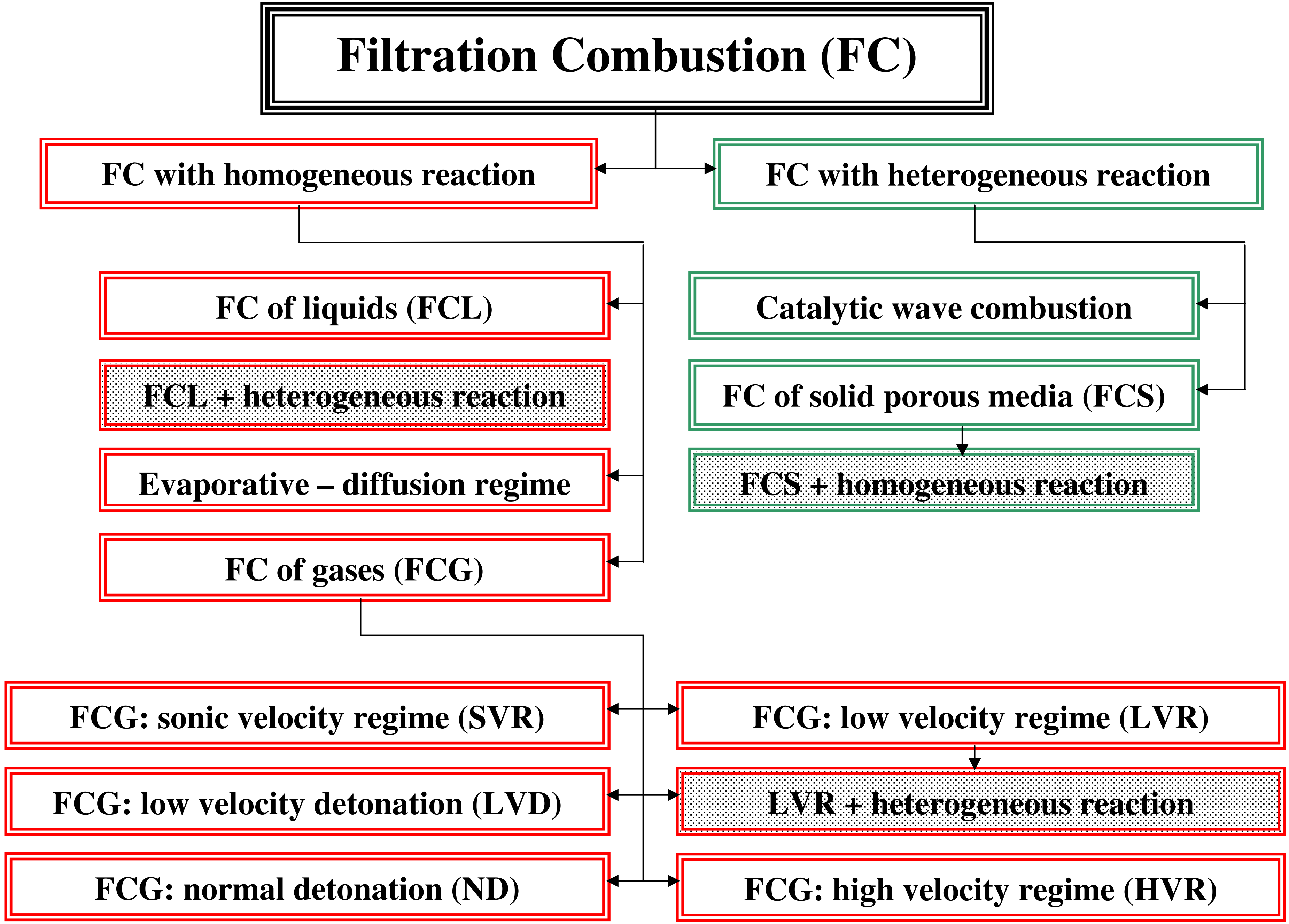


Repeated obstacles



Porous media

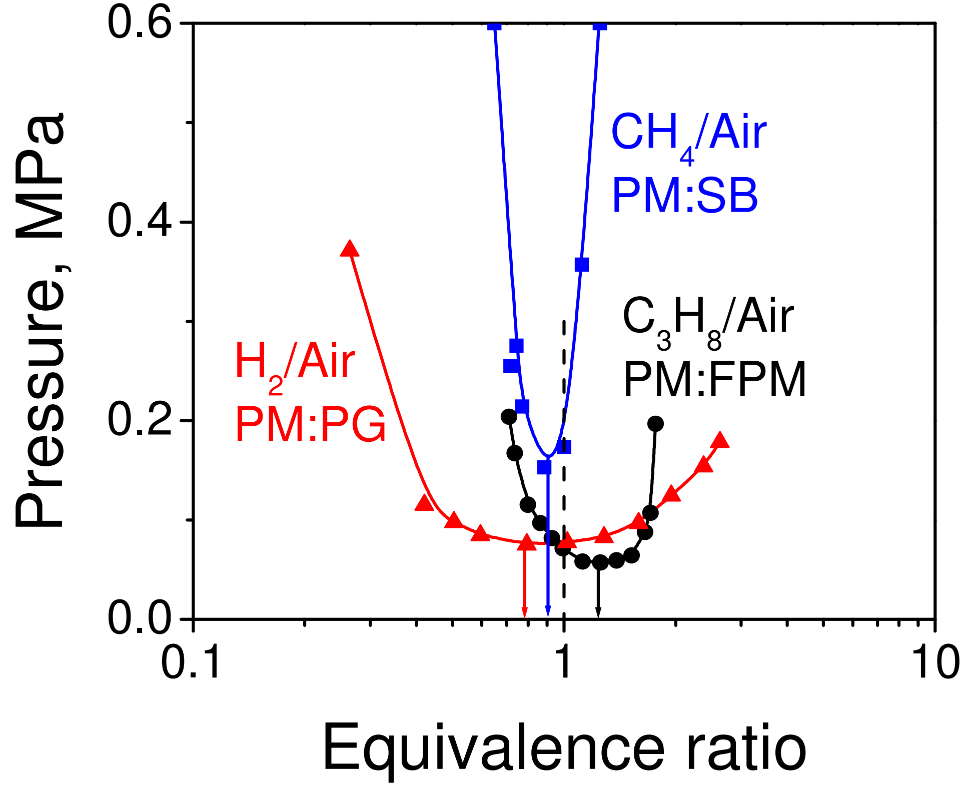


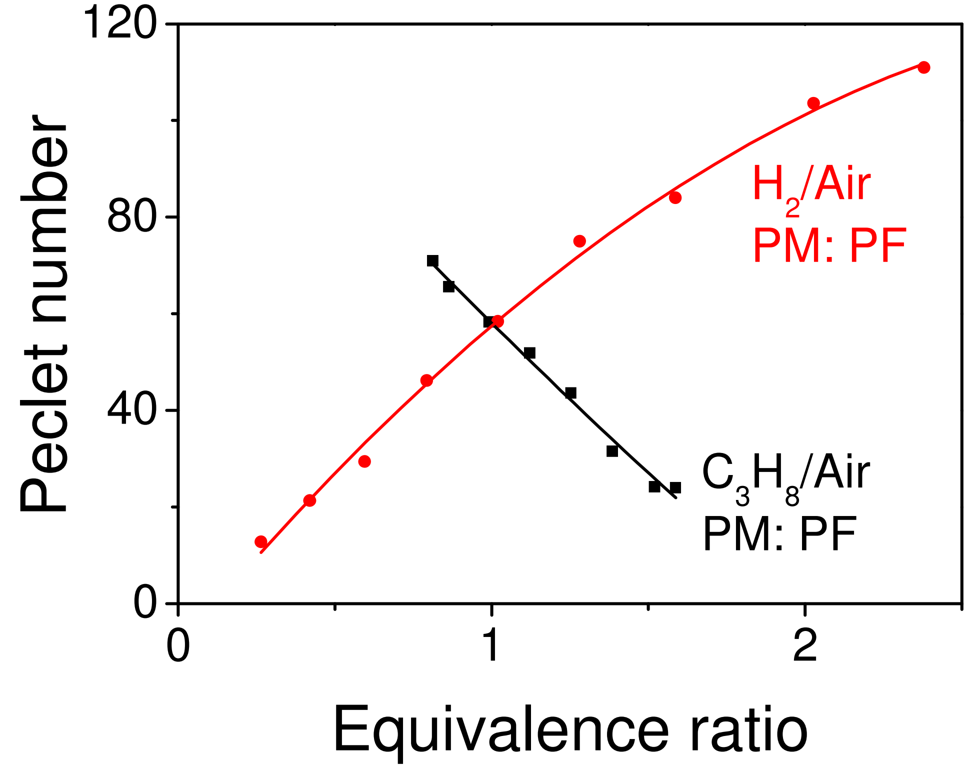

Filtration Combustion (FC)
FC with homogeneous reaction
FC with heterogeneous reaction
FC of liquids (FCL)
FCL + heterogeneous reaction
Evaporative – diffusion regime
FC of gases (FCG)
Catalytic wave combustion
FC of solid porous media (FCS)
FCS + homogeneous reaction
FCG: sonic velocity regime (SVR)
FCG: low velocity detonation (LVD)
FCG: normal detonation (ND)
FCG: low velocity regime (LVR)
LVR + heterogeneous reaction
FCG: high velocity regime (HVR)

REGIMES AND CHARACTERISTICS OF COMBUSTION AND DETONATION WAVES IN POROUS MEDIA

The regime	Typical wave velocity	Pressure in the wave, p/p_0	Propagation mechanism
Low velocity regime, (LVR)	10^{-4} m/s	1	conductive
High velocity regime, (HVR)	(1-50)Su	1	convective
Sonic velocity regime, (SVR)	(0.05-0.5)D_{C-J}	3-10	convective at higher p and T
Low velocity detonation, (LVD)	(0.5-0.9)D_{C-J}	10-30	convective with compression ignition
Normal detonation with heat and momentum losses, (ND)	(0.9-1.0)D_{C-J}	20-40	compression ignition

FLAMMABILITY LIMITS IN POROUS MEDIA





Corrections of mixture composition in leading points of flame front

$$\phi^{corr} = \phi + \Delta\phi,$$

$$\Delta\phi = k\phi\left(1-\phi\frac{D_{ox}}{D_f}\right) = k\phi\left(1-\phi\frac{Le_f}{Le_{ox}}\right) \qquad \phi \le 1$$

$$\Delta\phi = k\phi\left(\frac{1}{\phi}\frac{D_f}{D_{ox}}-1\right) = k\phi\left(\left(\phi\frac{Le_f}{Le_{ox}}\right)^{-1}-1\right) \qquad \phi \ge 1$$

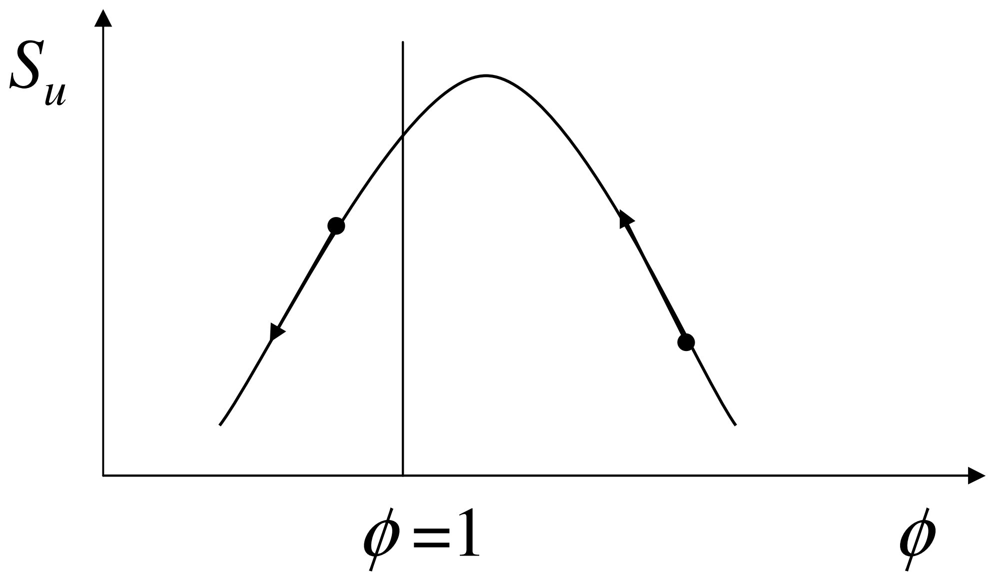
Corrections of burning velocities in leading points of flame front

$$S_u^{corr} = S_u\left(\phi^{corr}\right)$$

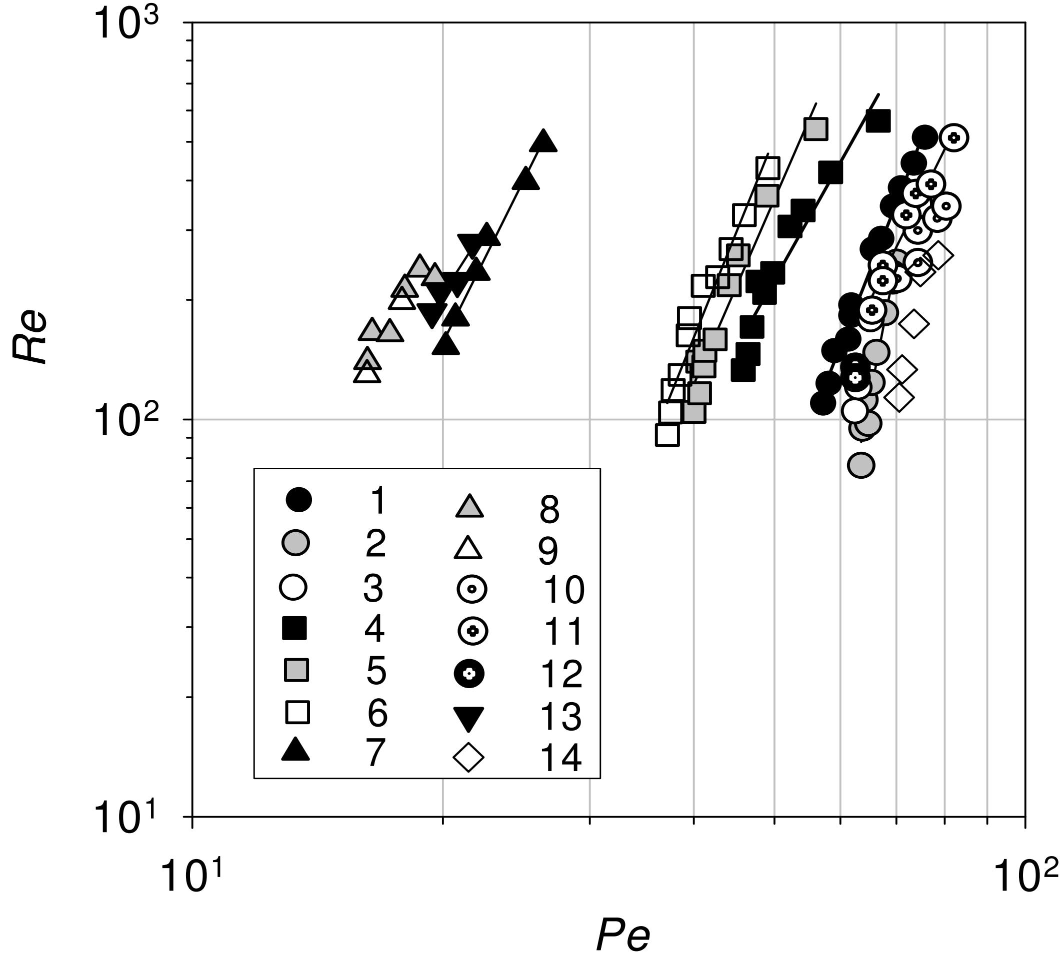
k – a constant for whole range of ϕ

k=0.22 for propane/air mixtures

$$Pe^{corr} = \frac{S_u^{corr} d}{\kappa}$$

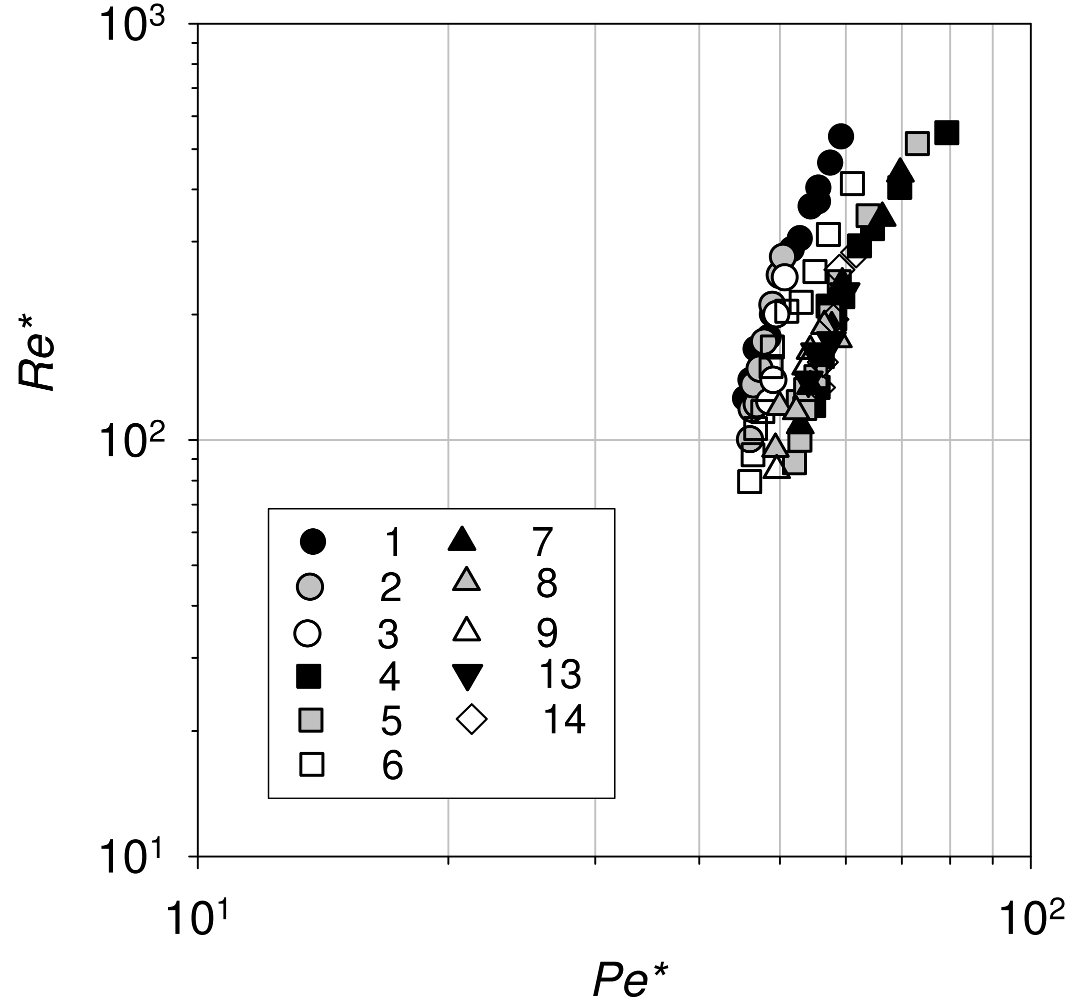


LEWIS NUMBERS EFFECTS WITHOUT CORRECTION



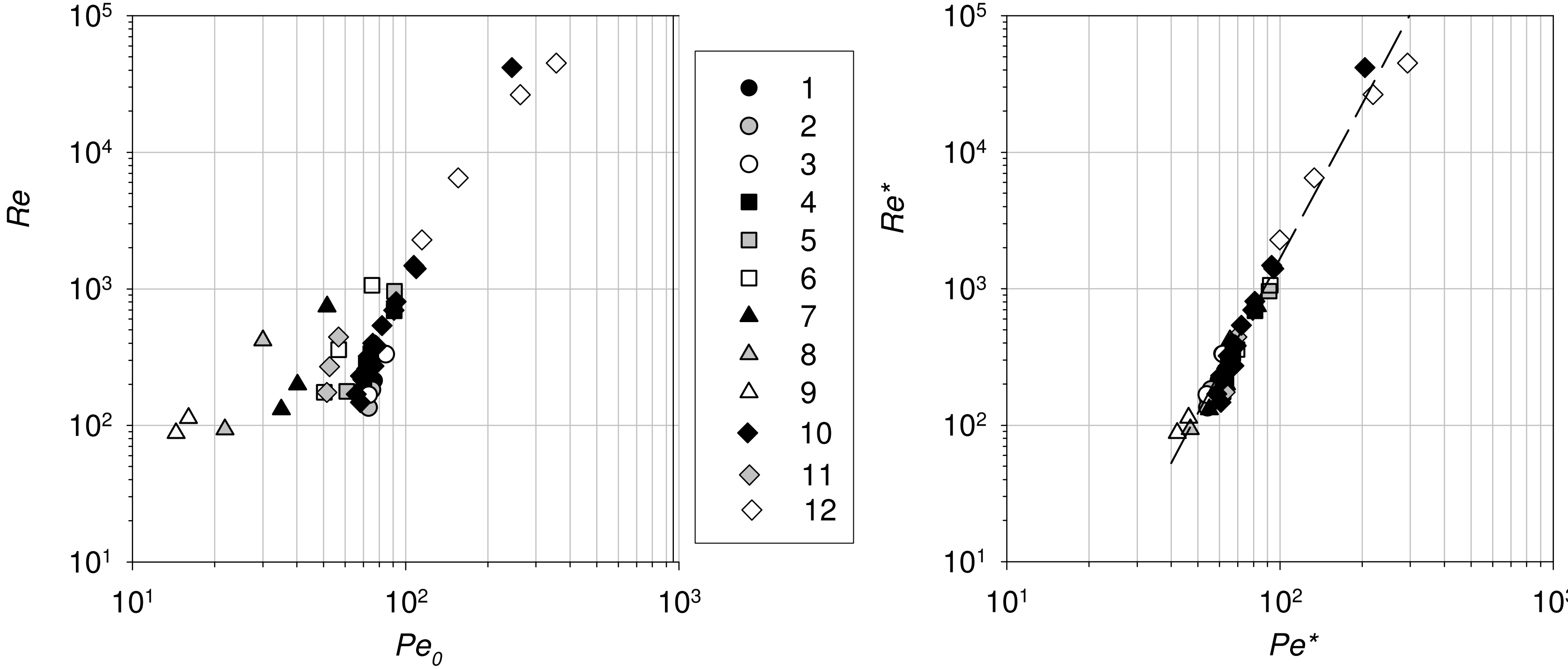
Dependencies of Re(Pe) under combustion of $C_3H_8/N_2/O_2$ mixtures at different initial pressures in polyurethane foam

LEWIS NUMBERS EFFECTS WITH CORRECTION



Dependencies of Re*(Pe*) under combustion of $C_3H_8/N_2/O_2$ mixtures at different initial pressures in polyurethane foam

LEWIS NUMBERS EFFECTS



Dependencies of Re(Pe) and Re*(Pe*) under combustion of C3H8/Air mixtures at different initial pressures and equivalence ratios in porous media

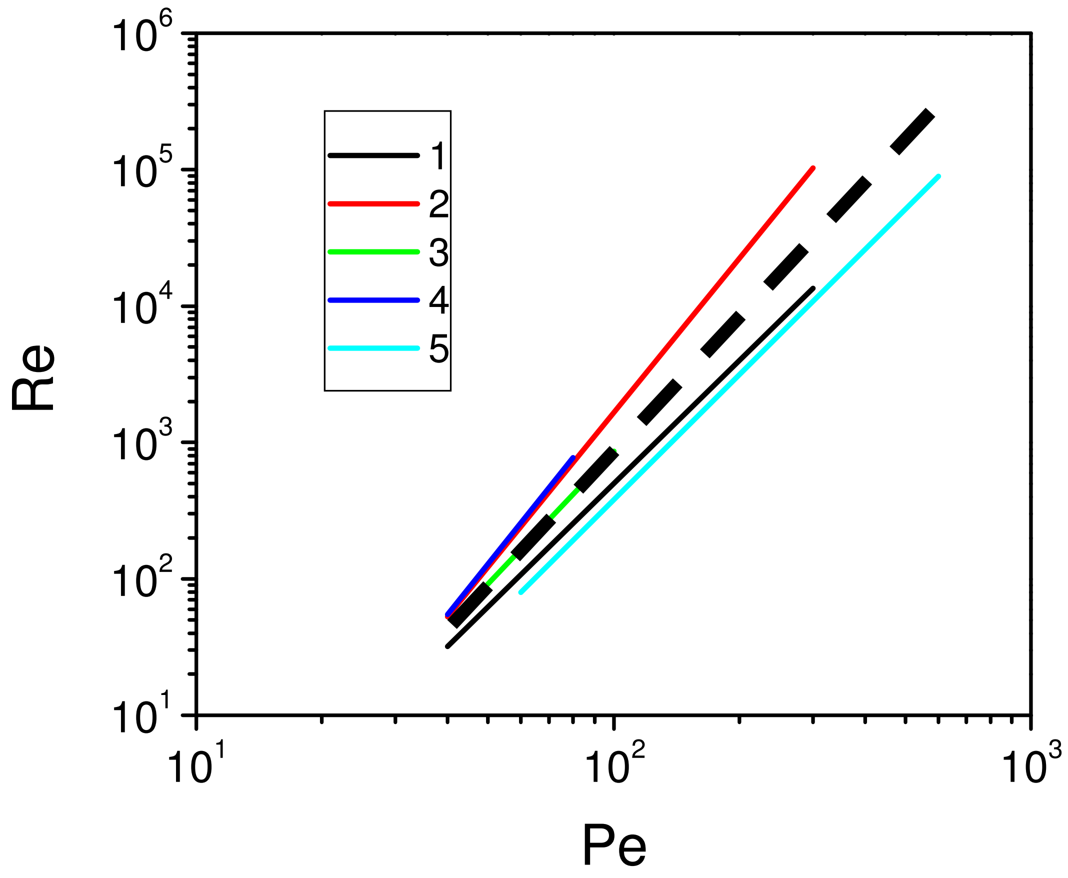
Left – without correction on Le Number

Right – with correction on preferential diffusion

Propane concentrations: 3.25% - 1; 3.50% - 2; 3.75% - 3; 4.03% -4, 10, 12; 4.5% -5, 5.0% - 6, 11; 5.5% -7, 6.0 – 8, 6.5 – 9.

Characteristic pore size: 4 mm – 1-9; 2.8 mm – 10, 11: 3 mm – 12.

TERMINAL VELOCITIES IN HIGH VELOCITY REGIME



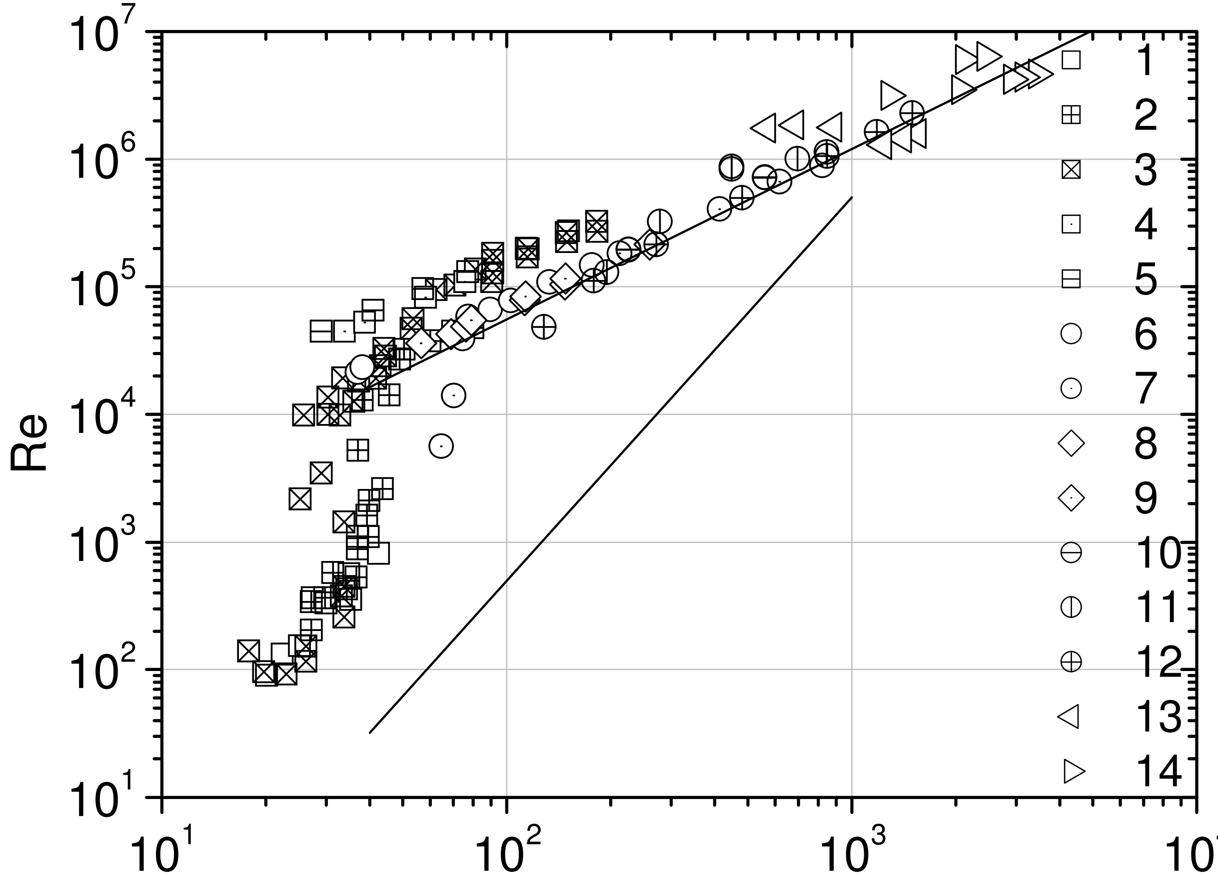
Dependencies Re(Pe) for various systems in HVR. 1- methane-air, 2 - propane-air, 3, 5 - hydrogen-air, 4 – propane-oxygen-nitrogen

EXPERIMENTAL DATA ON SVR

System	No in Figs.	fuel, %vol.	Pressure range, MPa	Pore size, cm	Flame velocity, m/s
Steel balls bed, hydrogen-air	1	15	0.2 - 0.42	0.09	1.2 – 3.8
	2		0.14 – 0.24	0.18	1.7 – 108
	3		0.04 – 0.4	0.41	1.1 – 360
	4	20	0.08 – 0.4	0.09	540 – 780
			0.11 – 0.4	0.18	550 – 650
	5	29.6	0.03 – 0.35	0.41	80 – 1010
	6		0.084 – 0.40	0.09	540 - 780
	7	50	0.075 – 0.35	0.18	650 – 840
	8		0.18 – 0.40	0.09	630 - 720
	9	29.6	1	0.46	800 – 810
				1.14	1195 – 1205

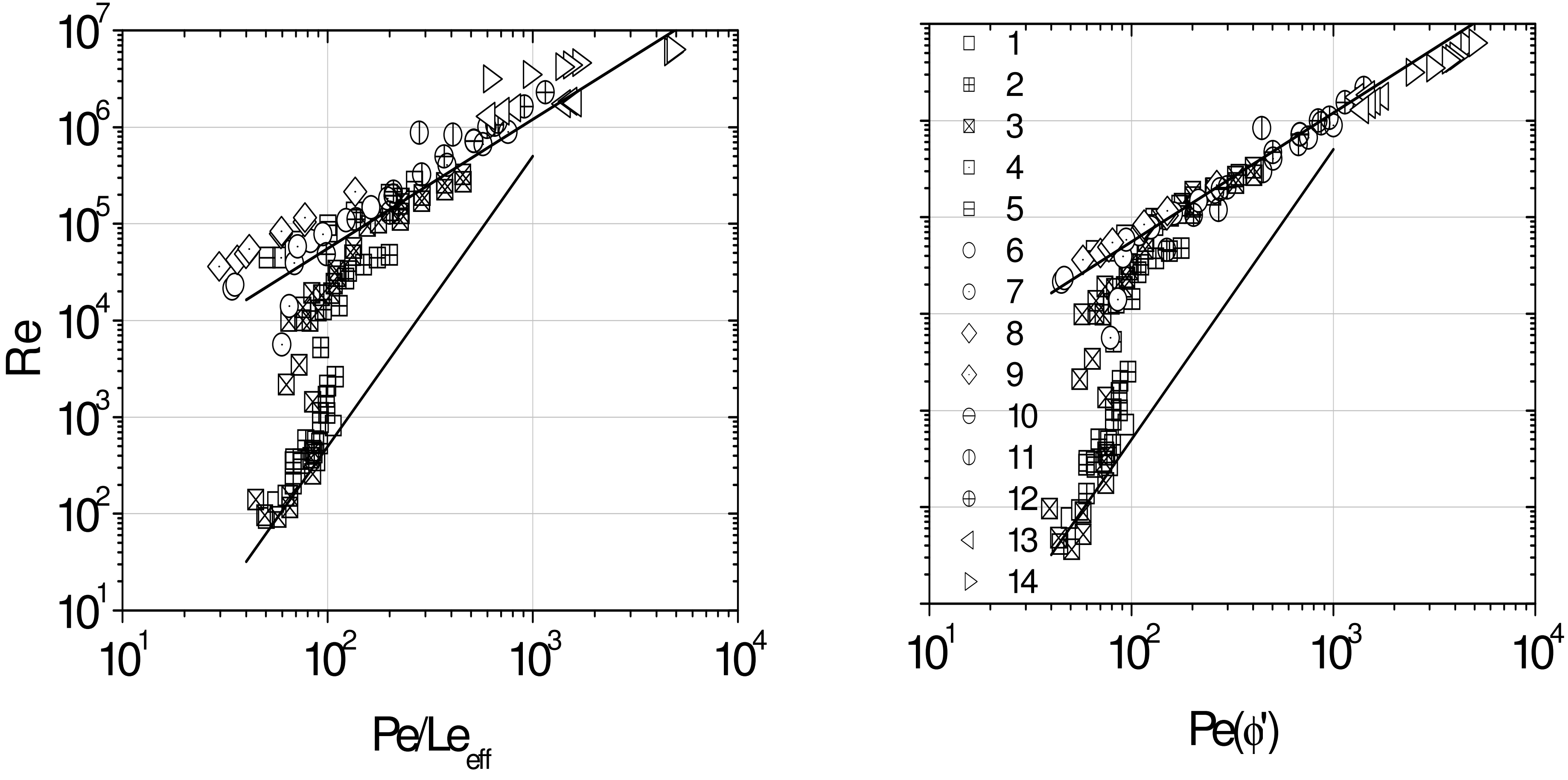
System	No in Figs.	fuel, %vol.	Pressure range, MPa	Pore size, cm	Flame velocity, m/s
Tubes with obstacles, hydrogen-air	10	15	0.05	1.75	520
				2.2	640
	13	18 – 55	1	3.8	810 – 1035
	14	18 – 70		11.7	850–1115
Multi chamber system, propane-air	12	4.0	0.02 – 0.4	2.4	150 – 350
	11	3.0	0.2		270
		4.5			350
		5.0			310
		5.5			190
		6.0			100
		6.5			40

TERMINAL VELOCITIES IN SVR WITHOUT LEWIS NUMBER CORRECTIONS



Numbers right – numbers of series of experimental data of different mixtures and initial conditions in SVR
Lower line – generalization of experimental data on CH_4/Air mixtures in HVR

LEWIS NUMBER CORRECTIONS OF TERMINAL VELOCITIES IN SVR



Left: effective Le Number approach
Right: preferential diffusion approach

TYPICAL RATE OF PRESSURE DISCHARGE FROM THE COMBUSTION ZONE

$$u\frac{du}{dx} = -\frac{1}{\rho}\frac{dp}{dx} - \lambda\frac{u^2}{2d}$$

$$\xi = \frac{\gamma\lambda L^*}{d} = \frac{1}{M_0^2} - 1 - \frac{\gamma+1}{2}\ln\frac{1+\frac{\gamma-1}{2}M_0^2}{\frac{\gamma+1}{2}M_0^2}$$

$$at\ M_0 << 1, \quad u_0 = \frac{a_0}{\sqrt{\xi+1}}$$

λ – **drag coefficient**

d – **typical pore size**

L^* – **combustion zone length**

u_0 – **typical rate of pressure discharge**

$M_0 = \frac{u_0}{a_0}$ – **Mach number**

CONDITIONS FOR IMPLEMENTATION OF HVR AND SVR

$$\sigma = \frac{S_{ut} Q}{u_0 c_p T_0} = \frac{S_{ut}\left(E - 1\right)\sqrt{\xi + 1}}{a}$$

HVR: $\sigma < 1$

SVR: $\sigma > 1$

Q – heat release

S_{ut} – turbulent burning velocity

E – expansion ratio

ξ – drag parameter

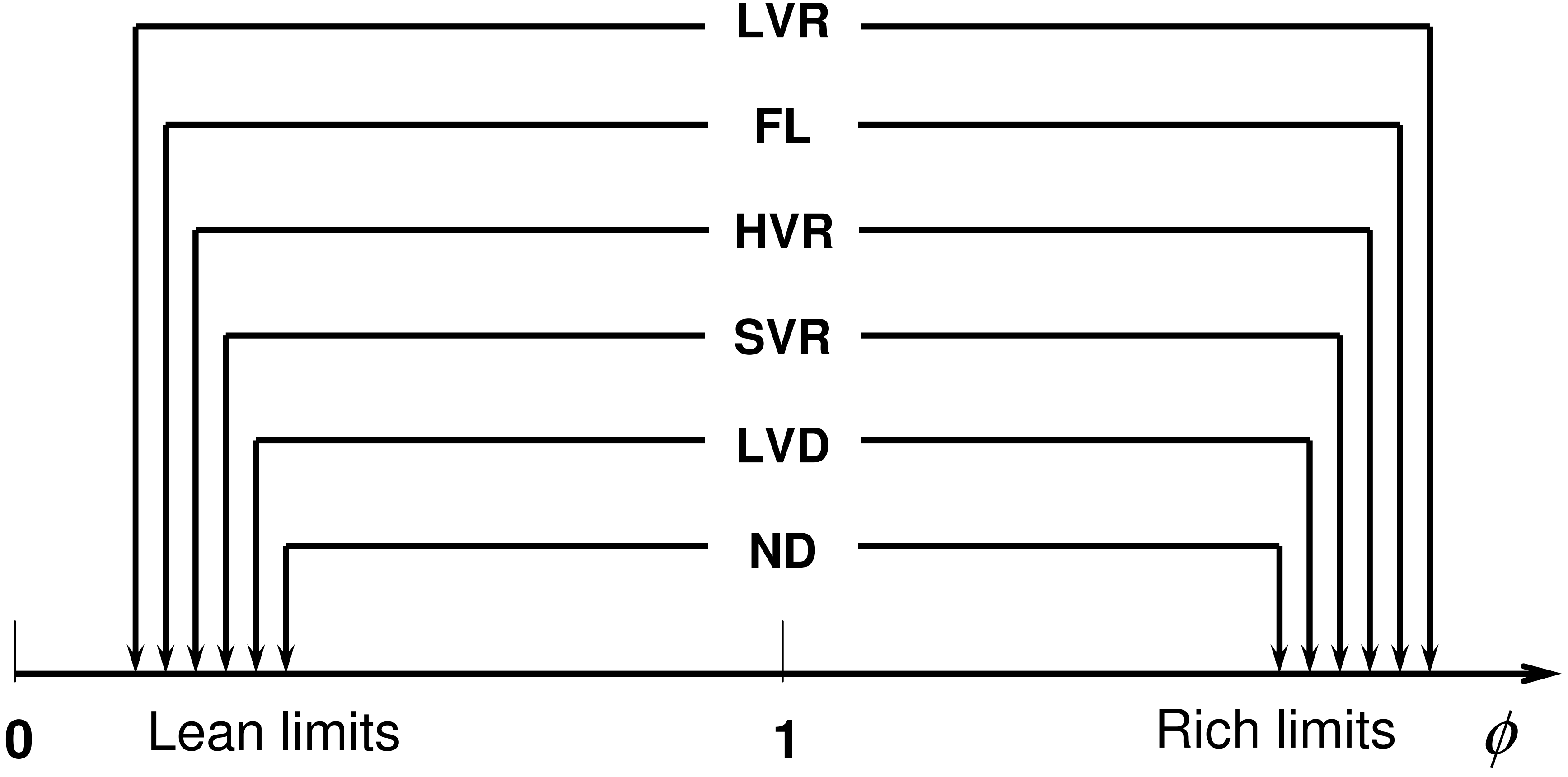
a – sonic velocity

GENERALIZED RELATIONSHIPS FOR HVR AND SVR

HVR: $Re = 6 \cdot 10^{-4} Pe^{3}$

SVR: $Re = 120 Pe^{4/3}$

“ENCLOSING PRINCIPLE”



SCHELKIN “SPIRAL”

Schelkin have found:
“in the very rough tubes the normal detonation is impossible, it transforms in combustion, which velocity can be controlled in wide range values from the detonation velocity to the approximately half value of it.”

K.I.Schelkin. “Fast combustion and spin detonation of gases”. Moscow , 1949.

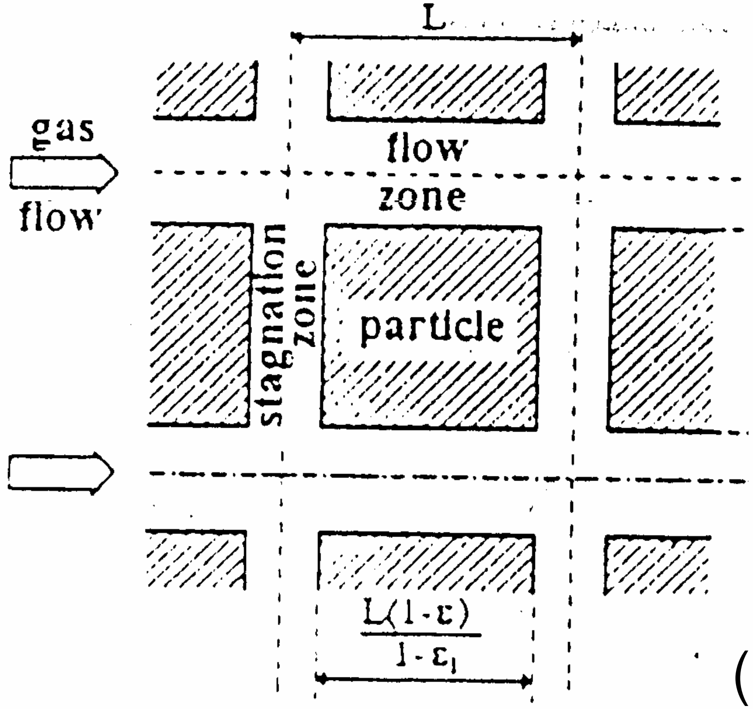
GAS COMBUSTION IN INERT POROUS MEDIA

(Filtration gas combustion)

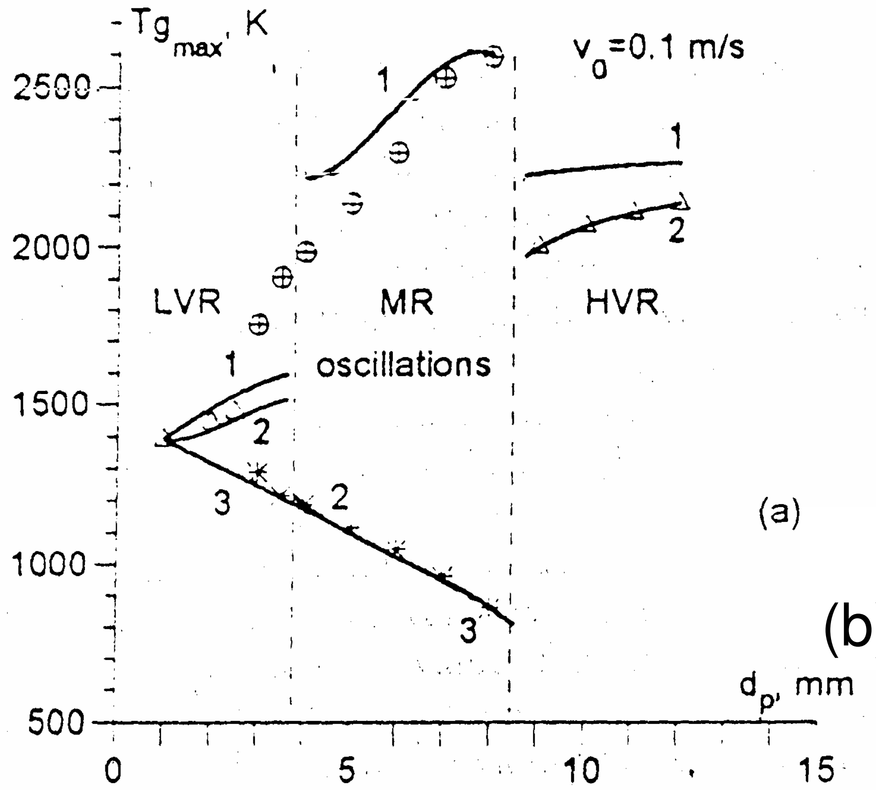
Steady-state combustion regimes:

1. Low velocity regime, LVR, $u \cong 10^{-4}$ m/s
2. High velocity regime, HVR, $S \cong 10$ m/s
3. Sonic velocity regime, SVR, $S \cong 10^{2}$ m/s
4. Low velocity detonation, LVD $D \cong 800\text{-}1500$ m/s
5. Normal detonation with losses, ND, $D \cong 1500\text{-}2500$ m/s

NONHOMOGENEOUS POROUS MEDIUM



(a)

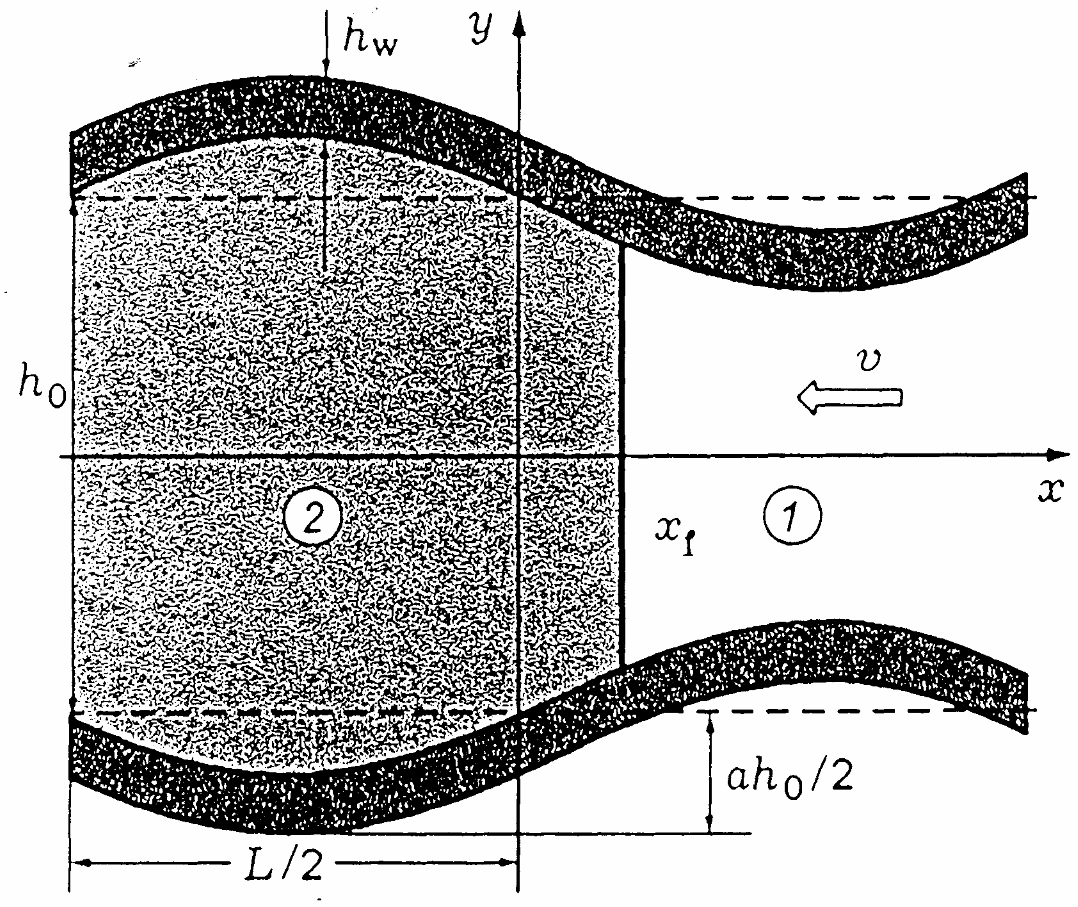


(b)

a) Sketch of the model of a porous medium with discrete periodic structure.
b) Effect of diameter of a solid particle, d_p, on the combustion wave temperature:
1,2 - the maximal and minimal values of $T_{g,max}$ in the discrete model;
3 - $T_{s,max}$; symbols relate to the continuous model.

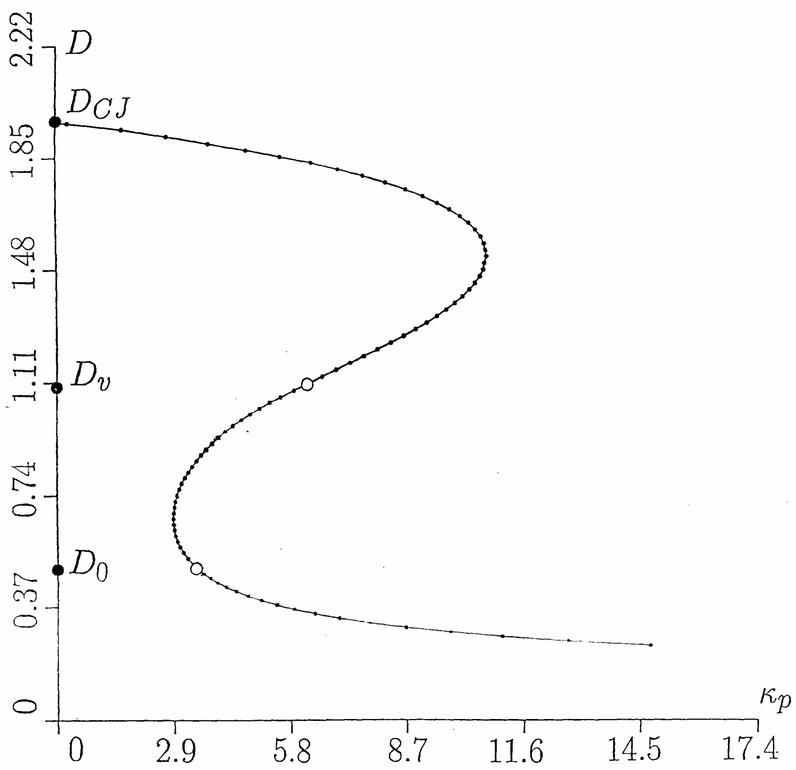
- *O.S.Rabinovich, A.A.Fefelov, N.V.Pavlyukevich.*
  Proc of 26-th Symp. (Int.) on Combustion, (1996), p.3383-3389.

NONHOMOGENEOUS POROUS MEDIUM



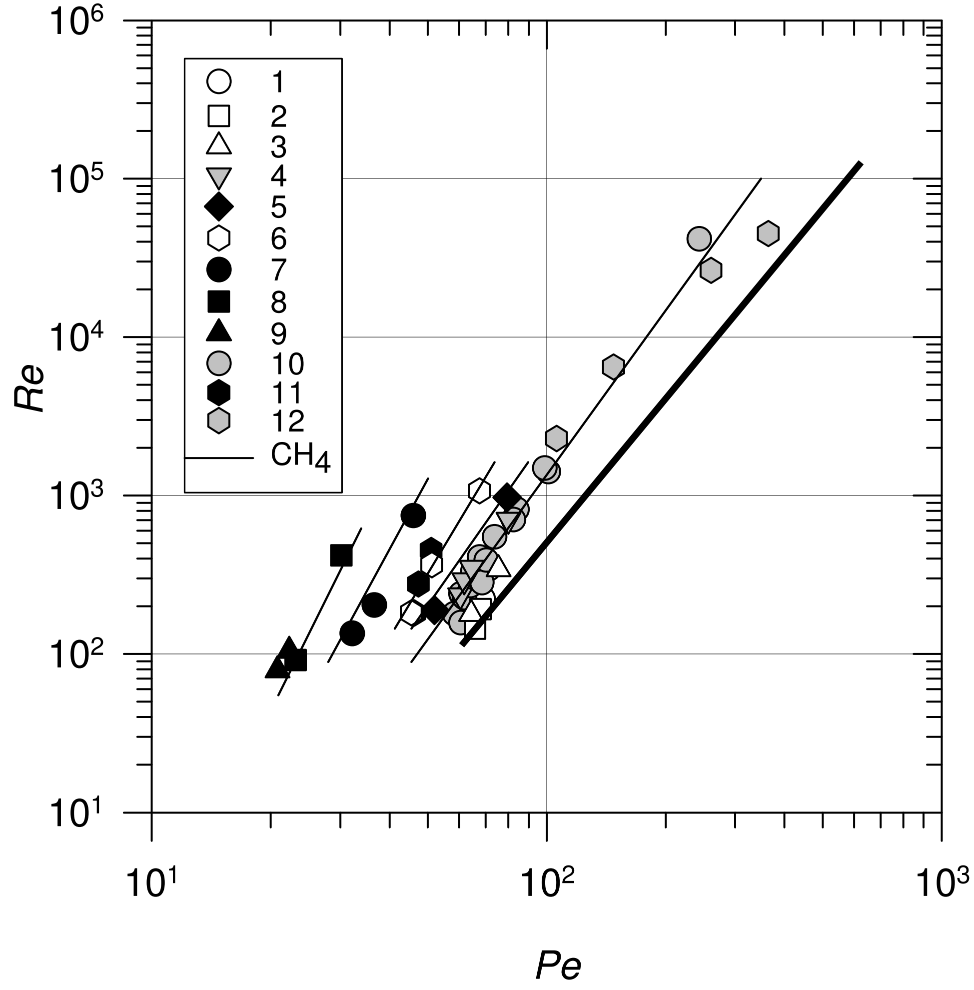
Flame structure: regions 1 and 2 refer to fresh mixture and combustion products, respectively.

MULTIPLICITY OF REGIMES



- *I.Brailovsky, L.Kagan, G.Sivashinsky*
  Proc. of Intern. Colloquium on Control of Detonation Processes, Moscow, Russia (2000)

LEWIS NUMBERS EFFECTS WITHOUT CORRECTION



Dependencies of Re(Pe) under combustion of C_3H_8/Air mixtures at different initial pressures and equivalence ratios in porous media

ANALYSIS OF EXPERIMENTAL AND THEORETICAL DATA

First group $Pe_{exp.}(\phi) - Le_{eff.,theor.}(\phi)$

Second group $Pe_{,exp.}(\phi) - Le_{eff.,exp.}(\phi)$

Third group $Pe_{theor.}(\phi) - Le_{eff.,theor.}(\phi)$

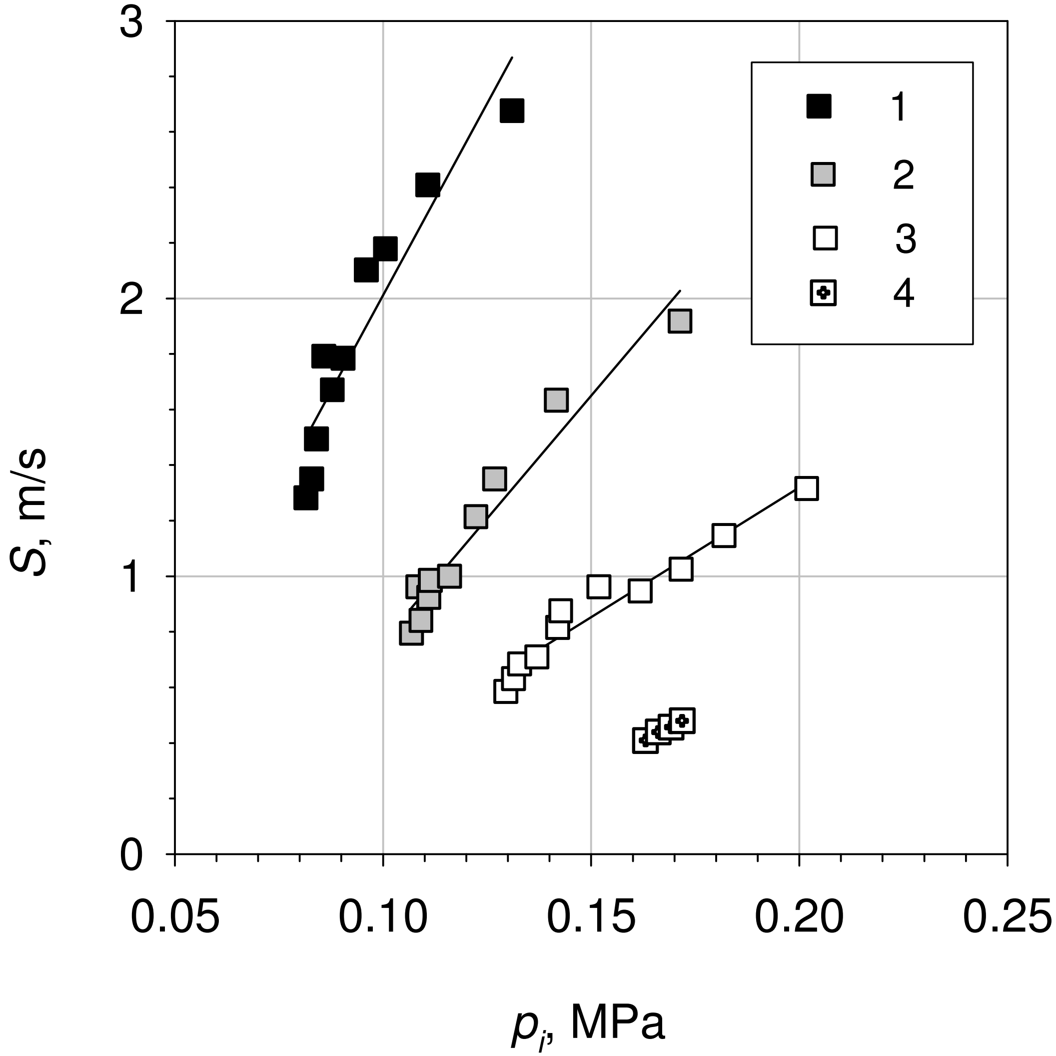
Results

$Le_{eff} \neq 1 \Rightarrow Pe_N = Le_{eff}$ This work -straight line

$Le = 1 \Rightarrow Pe_N = 1$ Zel'dovich results - dashes line

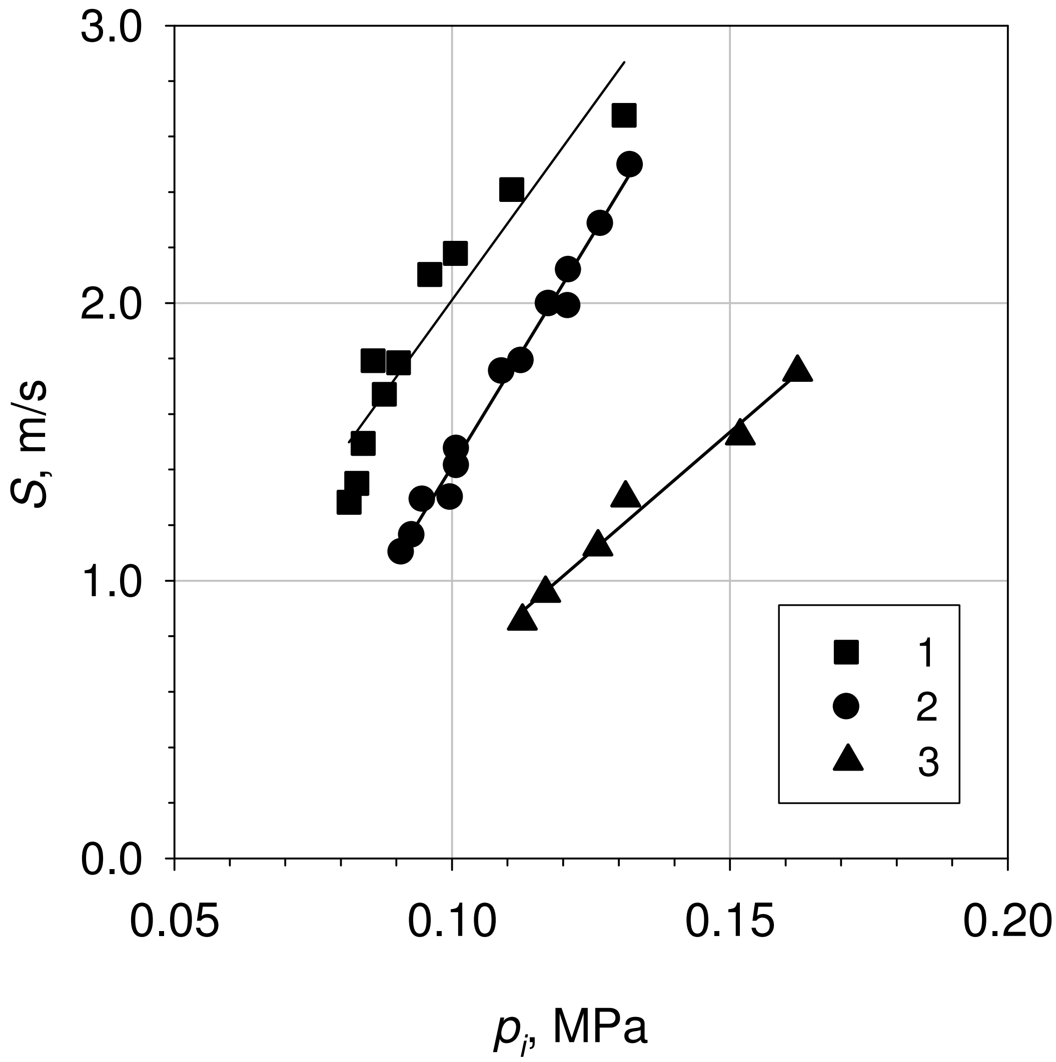
$$\left(Pe_{\max} / Pe_{\min}\right)_{\max} \cong 7$$

DEPENDENCIES OF FLAME SPEED ON INITIAL PRESSURE IN POLYURETHANE FOAM



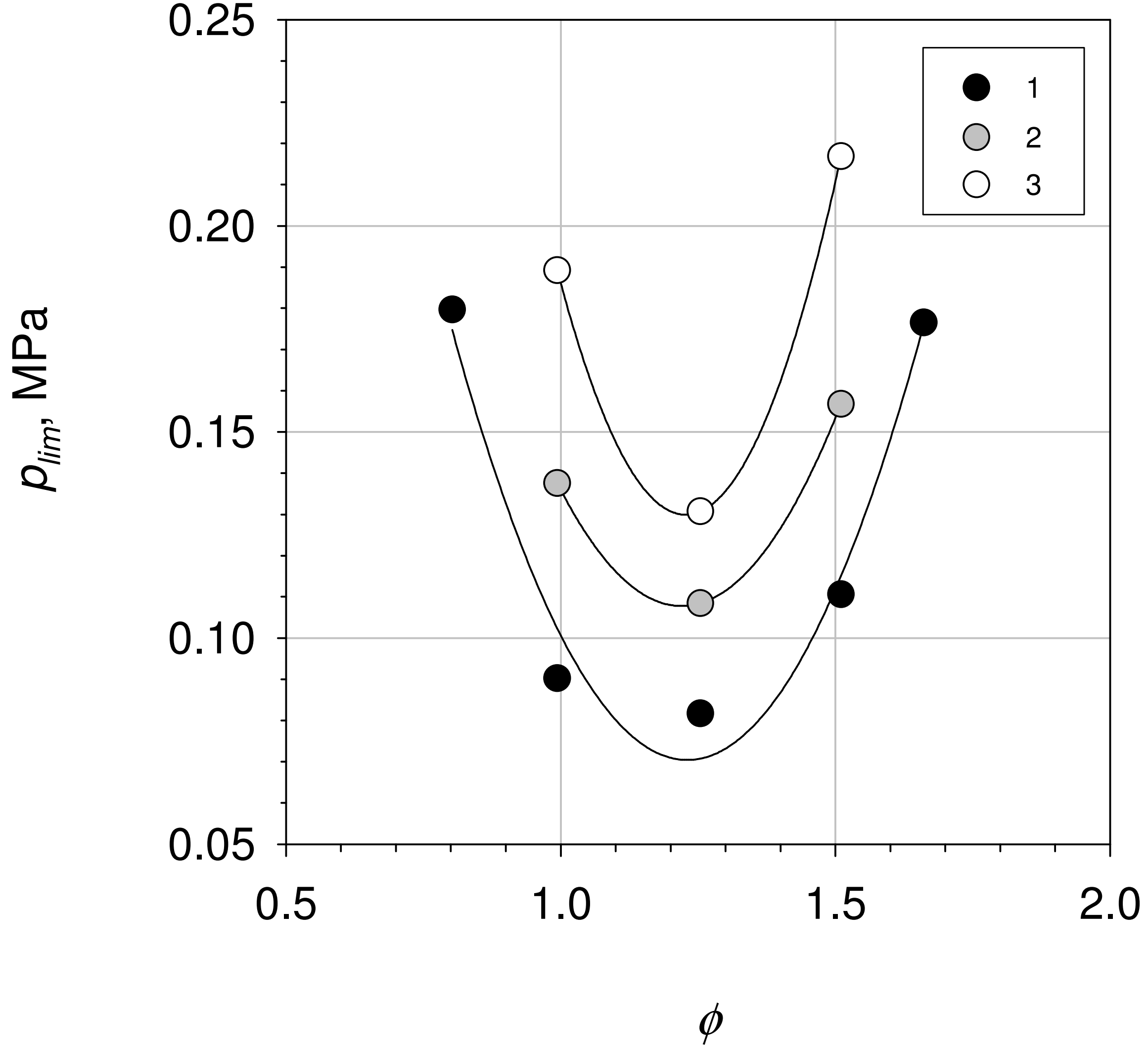
1 - 5% C_3H_8/air, 2 - 5% C_3H_8 /air + 10%N_2,
3 - 5% C_3H_8 /air + 15%N_2, 4 - 5% C_3H_8 /air + 20%N_2

DEPENDENCIES OF FLAME SPEED ON INITIAL PRESSURE IN POLYURETHANE FOAM



1 - 5% C_3H_8+air, 2 - 4% C_3H_8, 3 - 6% C_3H_8,

DEPENDENCIES OF LIMITING PRESSURE ON EQUIVALENCE RATIO IN POLYURETHANE FOAM



1 - C_3H_8/air, 2 - C_3H_8/air +10%N_2, 3 - C_3H_8/air +15%N_2