1. PRESSURE AND TEMPERATURE DEPENDENCE OF FLAMMABILITY LIMITS AND BURNING VELOCITY OF GASEOUS MIXTURES
2. THE DEPENDENCE OF PRESSURE INDEX OF BURNING VELOCITY OF GASEOUS MIXTURES ON CHEMICAL KINETICS IN THE FLAME FRONT

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ABSTRACT

Results of theoretical and experimental investigations of flammability limits and burning velocity of gaseous mixtures under increased pressuresand temperatures are presented.

Flammability limits were investigated at temperatures from 20 to 250°C and pressures from 0.1 to 2.0 MPa. Gaseous mixtures included the following components: hydrogen, oxygen, air, steam, nitrogen, argon, carbon dioxide, helium.

The burning velocities of gaseous mixtures, containing hydrogen, air and steam, were defined experimentally at temperatures from 20 to 200°C and pressures from 0.1 to 6.0 MPa. The effect of sign change of pressure index n of burning velocity S_u for values of S_u much greater, than 0.5 m/c, was found. It means, that the violation of Lewis-Elbe rule for the pressure index of burning velocity occures. Numerical modelling of flame propagation in stoichiometric methane-air and hydrogen-air mixtures mas executed with detailed chemical kinetics under room temperature and pressure in the range 0.1-2.0 MPa. The variation of rate constants k_i of following reactions was made :

$$H + H + M \rightarrow H_2 + M, \qquad (1)$$

$$O + O + M \rightarrow O_2 + M, \qquad (11)$$

$$H + O_2 + M \rightarrow HO_2 + M. \qquad (111)$$

Rate constantes k_i were reduced by a factor K, where K was 0.1, 1, 10, 100, 1000. The dependence of burning velocity and its pressure index on a factor K was investigated.

INTRODUCTION

The combustion characteristics of hydrogen-air-diluent mixtures at elevated pressures and temperatures are often needed for fire- and explosion safety in the process industry. The data for normal pressures P and temperatures T are rather complete, but the data for eleveted P and T are rather poor. The values of upper flammability limit (UFL) of hydrogen-oxygen-diluent (He, Ne, Ar, CO_2) at room temperature and pressure from 0.1 to 3.0 MPa were determined in [4]. In [5-8] the lower flammability limit (LFL) of stoihiometric hydrogen-oxygen mixture in diluents (steam, nitrogen, helium etc.) were determined at temperatures from 20 to 200°C and pressures from 0.1 to 2.0 MPa. But more complete data for combustion characteristics of hydrogen- contained mixtures at elevated pressures and temperatures are not sufficiently presented in literature. The purpose of this work is the investigation of combustion processes in hydrogen-oxygen-diluent mixtures (flammability limits, burning velocity) at pressures from 0.1 to 2.0 MPa and temperatures from 20 to 250°C . Theoretical interpretation of experimental results was made.

EXPERIMENTAL

Experiments for determination of flammability limits were performed in closed reaction steel vessel, which had the cylindrical form (diameter 300 and hight 800 mm).[7-8] The mixtures were created by partial pressures after vacuum-pumping of the reaction vessel and mixed by means of convectivie flows appearing due to slow temperature differences of reaction vessel walls. The ignition was made in the lower part of vessel by means of nichrim wire fusion due to electrical heating. The ignition energy was equal 10 J. Flame registration was made by means of thermocouples near the top of vessel and pressure transducer.

The burning velocity S_u for hydrogen-air-steam mixtures at high pressures and temperatures was measured in constant volume bomb, which had spherical form and volume of 4.2 l. The mixture obtained by partial pressures was initiated by means of nichrom wire fusion with the energy 1-2 J in the center of sphere. The pressure in the vessel during explosion was registrated by means of pressure transducer "Sapphire-22" with time constant of the order of $3*10^{-3}$ s. The burning velocity dependence from pressure and temperature was calculated according to method described elewhere[9]. This method is based on comparing of experimental and calculated (by means of closed vessel explosion model) dependence of pressure in the vessel during mixture explosion. This method gave a good agreement with the available experimental data for initial pressure of 0.1 MPa and room temperature.

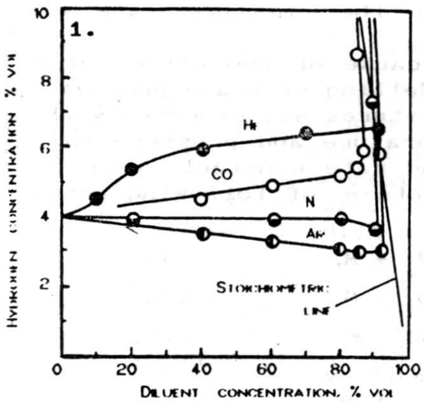
RESULTS AND DISCUSSIONS

The experimental data for flammability limits are shown in Fig.1-3. From Fig.1-3 some conclusions can be made. Among the diluents investigated (CO_2, H_2O, N_2, Ar) the most efficient is the gas with the largest molar heat capacity (CO_2). But the behavior of lower flammability limits for hydrogen-oxygen-helium mixtures is unusuall the dependence of hydrogen concentration at low flammability limit on diluent concentration is sufficiently nonlinear. This effect is due to the bubble character of flame propagation in very lean (from 4 to 8 % (val.)) hydrogen-oxygen respect with oxygen and other diluents investigated and high thermoconductivity coefficient for helium.

Some experimental data for lower flammability limits of hydrogen-oxygen-composite duluent (helium + steam, helium + carbon dioxide, nitrogen + carbon dioxide) are presented in Fig.4.

It is evident that additive empirical rule for flammability limits in the case of composite diluent contained helium is disturbed. This effect is caused by high thermoconductivity coefficient of helium and bubble character of combustion of very lean hydrogen-air mixtures mentioned above.

The dependence of burning velocity of hydrogen-air-steam mixture on pressure at various temperatures is shown in Fig.5. It can be seen that addition of a small quantity of steam ($\sim$5 % (vol.))



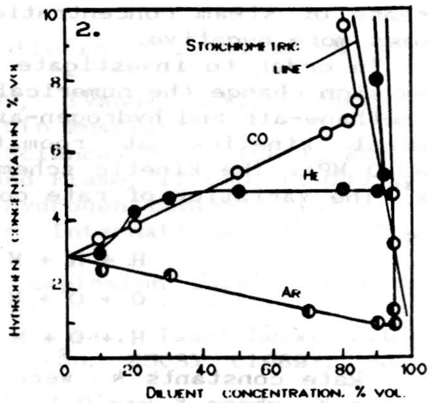
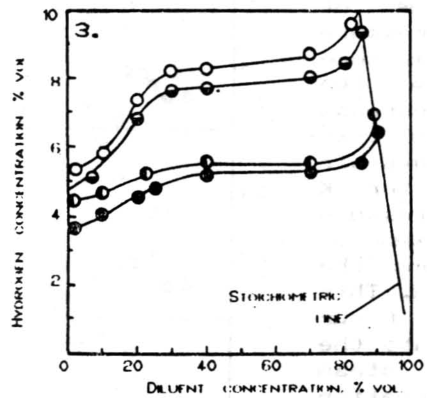


Fig.1. Flammability limits of hydrogen-oxygen-diluent mixtures at temperature 20°C and pressure 0.1 MPa.

Fig.2. Flammability limits of hydrogen-oxygen-diluent mixtures at temperature 250°C and pressure 0.1 MPa.



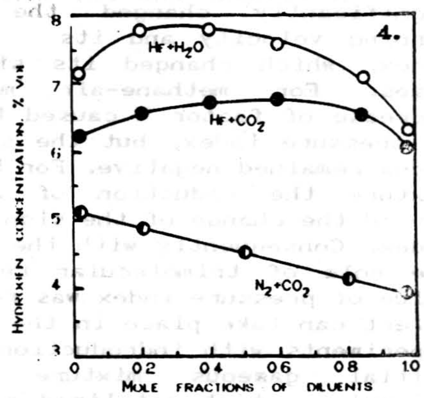


Fig.3. Flammability limits of hidrogen-helium-diluent mixtures at temperatures T and pressures P_o :
○ - P_o = 20 MPa, T = 20°C; ◐ - P_o = 0.6 MPa, T = 20°C;
◒ - P_o = 2.0 MPa, T = 250°C; ● - P_o = 0.6 MPa, T = 250°C.

Fig.4. Lower flammability limits as a function mole fractions the first diluen component in diluent mixtures at temperatures and pressures :
(He-H_2O) - P_o = 0.6 MPa, T = 250°C ;
(He-CO_2) - P_o = 0.1 MPa, T = 20°C;
(N_2-CO_2) - P_o = 0.1 MPa, T = 70°C.

causes change of sign of pressure index n in the expression for pressure dependence of burning velocity $S_u = S_{uo}(P/P_o)^n$. With the increase of steam concentration in the mixture the value of n becomes more negative.

In order to investigate the cause of the effect of pressure index sign change the numerical modelling of flame propagation throw the methane-air and hydrogen-air mixtures was executed with detailed chemical kinetics at room temperature and pressure in the range 0.1-2.0 MPa. The kinetic scheme and rate constants were taken from work[11]. The variation of rate constants k_i of following reactions was made:

$$H + H + M \rightarrow H_2 + M, \qquad (1)$$

$$O + O + M \rightarrow O_2 + M, \qquad (11)$$

$$H + O_2 + M \rightarrow HO_2 + M. \qquad (111)$$

Rate constants k_i were reduced by a factor K, where K was 0.1, 1, 10, 100, 1000. The dependence of burning velocity and its pressure index on a factor K was investigated. It was found that the variation of k_i for the reaction (1) and (11) in pointed range had relatively small influence on burning velocity. In this case the sign of pressure index was not change, but the change of rate constant of reaction (111) significantly changed the value of burning velocity and its pressure index, which changed its sign in some cases. For methane-air mixture the increase of factor K caused the increase of pressure index, but the sign of this index remained negative. For hydrogen-air mixture the reduction of a factor K caused the change of the sign of pressure index. Consequently with the increase of the role of trimolecular reactions the value of pressure index was reduced. This effect can take place in the case of our experiments with indroduction into the initial gaseous mixture the steam molecules, which catalised recombination reactions[12].

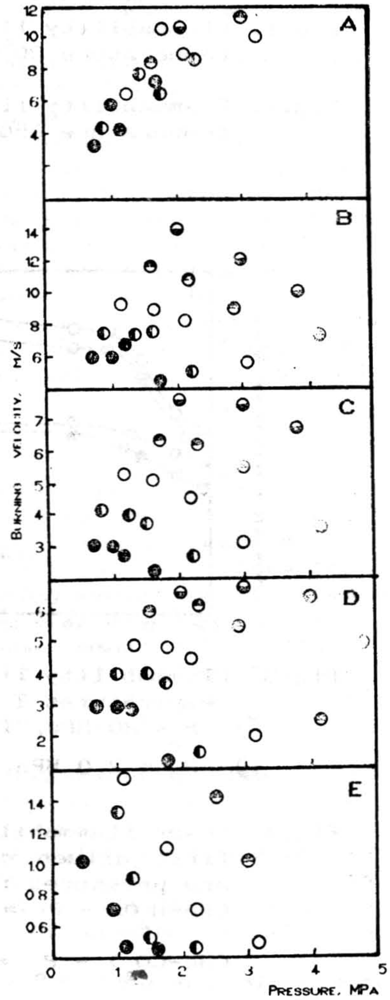


Fig.5. The dependence of burning Su from pressure P at various temperatures T and concentrations of steam C_{H_2O}:
a) C_{H_2O} = 0 % vol.; b) C_{H_2O} = 5 % vol.; c) C_{H_2O} = 10 % vol.; d) C_{H_2O} = 20 % vol; e) C_{H_2O} = 30 % vol.
● - T = 200°C; ◐ - T = 250°C; ○ - T = 300°C; ◓ - T = 350°C; ◒ - T = 400°C

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VENTING OF GASEOUS EXPLOSIONS: TURBULIZATION ASPECT

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ABSTRACT

The main goal of the present investigation is to discuss multiparametric dependence of turbulization factor χ on combustion and venting conditions in an vented vessels or other enclosures. More well grounded dimensionless formulae for minimal safe vent area calculation are cited, then those in the NFPA 68 "Guide for Venting of Deflagrations" (1988 Edition). Formula for turbulization factor χ dependence on the vessel volume V; "true" vent ratio $(F/V^{2/3})$; maximum dimensionless internal pressure π_m, that can be withstood by the weakest structural element; maximum dimensionless explosion pressure developed in unvented vessel π_e; and other conditions is given and discussed.

INTRODUCTION

According to *Industrial Risk Insurers* about 40% of the total explosions is a result of deflagration inside process equipment and buildings. Venting of deflagration - the main protection method, allowing to minimize structural and mechanical damage from combustion overpressure within an enclosures.

Practically all companies dealing with explosion protection systems, such as Fike Corp., Fenwal Inc. et al., use now for determination of the vent area NFPA 68 "Guide for Venting of Deflagrations". This document is based on large experimental material, but has some serious limitations. In particular it does not answer on the question: how initial turbulence, or turbulence-producing internal appurtenances influence on dynamics and hence on maximum pressure of explosion? Employment of NFPA 68 in such cases without new scientific knowledge will lead to catastrophes.

RESULTS AND DISCUSSIONS

The system of dimensionless differential equations, derived from energy and mass conservations laws, with "surface" turbulent combustion model was used by modeling[1]. According to Michelson's principle the main factor of vented deflagration - turbulization factor χ is determined as ratio of real area of turbulent flame surface at some moment to surface area of sphere to which burned products may be collected at the same moment (turbulent burning velocity $S_t=(f_t/f_s)S_u=\chi S_u$, where S_u - laminar burning velocity). It is self-evident, that for laminar spherical flame propagation $\chi=1$. But really $\chi>1$, because flame front is disturbing by different phenomenons: wrinkling flame structure due to hydrodynamic[2], acoustic[3] (or Taylor[4]) or diffusion-thermal[5] instabilities; convective deformation of combustion edge; initial mixture turbulence or flame turbulence, produced by combustion products or obstacles and so on.

Origin and development of wrinkling flame structure gives $\chi=1.5\div2$, as experiments in 70 m^3 initial volume rubber bubble[6] and our researches showed.

Under isotropic turbulence[7] maximum value of turbulization factor is equal χ=4÷6. Further rise in the isotropic turbulence intensity causes flame extinction at the Karlovits criteria $\frac{v'}{S_u}\frac{\delta l}{l}$=10÷20 ($v'$ - pulsating velocity; δl - laminar flame front depth; l - turbulence scale).

A maximum ratio of visible burning velocity ahead of and behind three meshes (0.8 mm wire diameter, 1.6 mm mesh size) in laboratory conditions[8] is equal to 12. For respectively large-scale experiments[9] in 11 m^3 volume vessel with only one grid (18 mm wire diameter, 125 mm mesh size) we obtain already χ=14.

Dependence of safe vent area F, which contains in venting parameter W, on turbulization factor χ is given by our engineering dimensionless formulae, obtained on the base of system of exact differential equations, respectively for subsonic and sonic ($2 \le \pi_m \le \pi_e$) efflux:

$$W=\frac{\chi(E_i-1)}{E_i^{1/2}\sqrt{\pi_m-1}}, \qquad (1)$$

$$W=0.9\frac{\chi(\pi_e-\pi_m)}{E_i^{1/2}}, \qquad (2)$$

where dimensionless venting parameter $W=\frac{1}{(36\pi_o)^{-1/3}\sqrt{\gamma_u}}\frac{\mu F}{V^{2/3}}\frac{C_{ui}}{S_{ui}}$ with π_o - "pi" number, μ - discharge coefficient, C_{ui} - speed of sound; E_i - combustion products expansion coefficient at initial conditions; $\pi_m=p_m/p_i$ - maximum dimensionless pressure, which a sheath of a vessel or other enclosure can withstand (maximum explosion pressure in case of inverse problem, when vent area is known); $\pi_e=p_e/p_i$- dimensionless adiabatic explosion pressure in closed vessel. Relief vent diameter determination error when using formulae (1), (2) is near 10% in comparison with exact computer solution of system of differential explosion dynamics equations.

Hence, the mistaken choice of χ, for example in 5 times, will cause the same - in our case 5 times error in safe vent area determination. It's obviously the way to catastrophes.

Generalization of Russian and world experience in venting of deflagration field permitted us to obtain formula for turbulization factor dependence on the vessel volume V; "true" vent ratio $F/V^{2/3}$; dimensionless maximum internal pressure π_m, that can be withstood by the weakest structural element; dimensionless maximum explosion pressure in closed vessel π_e

$$\chi=(1+a_1V)(1+a_2\frac{F}{V^{2/3}})(a_3+a_4\frac{\pi_e-\pi_m}{\pi_e-2}) \qquad (3)$$

with empirical coefficients a1, a2, a3, a4 from Table for different conditions.

Table. Empirical coefficients for χ determination

Burning conditions	Empirical coefficients			
	$a1$	$a2$	$a3$	$a4$
Vessel volume $V \le 10$ м^3; vent ratio $F/V^{2/3} \le 0.25$	0.15	4	1	0
Maximum explosion pressure $1 < \pi_m < 2$:				
- uncovered vent	0	0	2	0
- covered vent	0	0	8	0
Maximum explosion pressure $2 \le \pi_m < \pi_e$:				
- uncovered vent	0	0	0.8	1.2
- covered vent	0	0	2	6

There is an influence of turbulization factor χ value on dynamics of vented deflagration shown on Fig.1 for laminar spherical (χ=1) and turbulent (χ>1) flame propagation. Pressure-time curves on Fig. 1 and 2 were obtained by using computer research program "DYNAMICS (Venting of Gaseous Explosions)", based on exact system of dimensionless differential equations of vented gas deflagration dynamics. Calculations for graphs on Fig.1 were made for near stoichiometric hydrocarbon-air mixture in 10 m^3 volume vessel with 0.5 m vent diameter and following parameters: initial and atmospheric pressure p_i=p_a=0.1 MPa; vent closure release pressure p_v=0.11 MPa; initial temperature and burning velocity respectively T_i=298 K and S_{ui}=0.34 m/s; adiabatic factors γ_u=1.365 and γ_b=1.248;

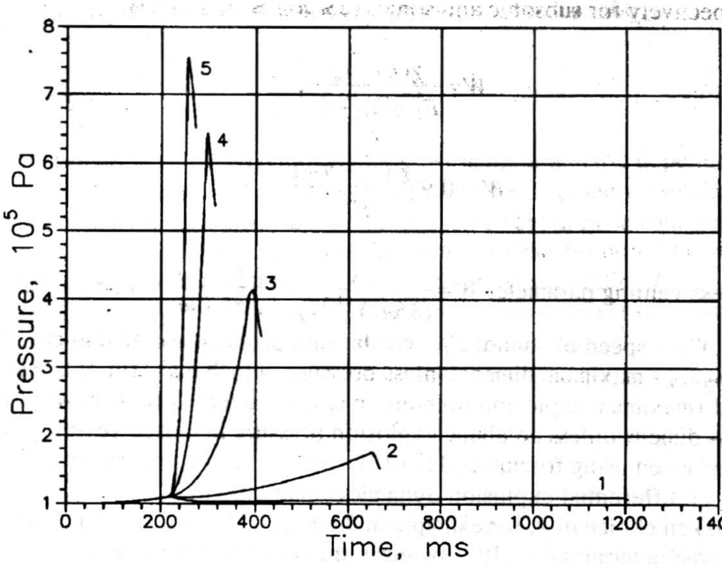

Fig.1 Dynamics of vented deflagration in 10 m^3 vessel with 0.5 m vent diameter for laminar (curve 1) and turbulent (curves 2÷5) flame propagation: 1 - χ=1; 2 - χ=2; 3 - χ=4; 4 - χ=8; 5 - χ=16.

thermokinetic factor ε=0.24; expansion ratio E_i=7.592; mixture molecular mass M=29.58; discharge coefficient μ=0.8; turbulization factor before vent closure release χ_o=1.

There is strong dependence of maximum explosion pressure and explosion duration from turbulization factor χ on Fig.1. With χ=16 the maximum pressure in vented vessel is near to it in unvented vessel.

What values of turbulization factor χ correspond to most widely using all over the world NFPA 68 "Guide for Venting of Deflagrations"? Comparison of NFPA 68 (4-3.1 paragraph) formula $F=\frac{CA_s}{(P_{red})^{1/2}}$ with our engineering formula (1) lead to equality for $C=\frac{1{,}86\chi S_{ui}}{T_{ui}^{1/2}}$ (kPa)$^{1/2}$. For such gases as propane we have C=0.45 (kPa)$^{1/2}$ from NFPA 68 table and with S_{ui}=0.42 m/s, T_{ui}=298 K we can get for Low-Strength Enclosures (capable of withstanding not more than 0.01 MPa in NFPA 68 terminology) practically constant value nearby χ=10. From one side it close to our value χ=8, obtained for "undefined" vented deflagration conditions by comparison of engineering formula (1) with well grounded graphical recommendations of D.Bradley and A.Mitcheson[10], based on large experimental material of different authors. But from other side, as last results of theory and experiments comparison showed[9], the value of χ changes in wide range χ=1÷14 and even more. Because of safe vent area F is proportional to χ, as formulae (1) and (2) show, NFPA 68 gives in some cases large vent area (χ<10) and in other cases fewer vent area (χ>10). In both occurrences the user (customer) will bear loss. The last case is the reason of catastrophes, when there is deflagration in an enclosure, if even there are vents.

There is an influence of vent area on explosion dynamics in 1000 m^3 enclosure for constant turbulization factor χ=10, corresponding to NFPA recommendations, on Fig.2. Hence, according to NFPA 68 for 10m × 10m × 10m enclosure capable of withstanding 0.005 MPa ga the safe vent diameter must exceed 8.5 m (see Fig.2). It's near 60% of one side area of that enclosure. But it's wrong

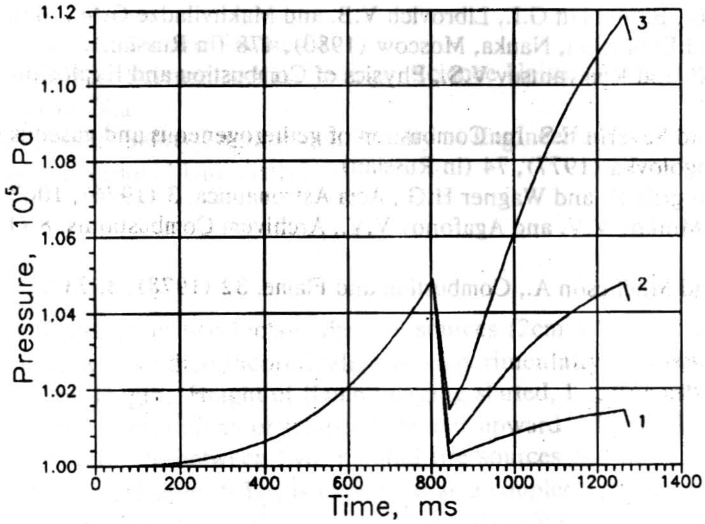

Fig.2 Dynamics of vented deflagration in 1000 m^3 enclosure for turbulent flame propagation with χ=10, corresponding NFPA 68, and different vent diameter: 1 - D=11.3 m (vent is one end of 10m × 10m × 10m enclosure); 2 - D=8.5 m; 3 - D=7 m.

for χ>10, what my be, for example, when there are obstacles within enclosure.

For High-Strength enclosures (reduced pressure P_{red}, i.e., the maximum pressure actually developed during a vented deflagration, is within the range 0.02-0.20 MPa in NFPA 68 terminology) the equality of formula $F=0{,}148\ (V)^{0{,}703}\ e^{0{,}942 P_{stat}}\ P_{red}^{-0{,}671}$ from 6-1.1.1 paragraph of NFPA 68 and our formula gives dependence for turbulization factor

$\chi=0{,}0165\ \frac{T_{ui}^{1/2}}{S_{ui}}\ \frac{V^{0{,}036}}{P_{red}^{0{,}171}}\ e^{0{,}942\ P_{stat}}$. For V=10 m^3 vessel and parameters: S_{ui}=0.34 m/s; T_{ui}=298 K; P_{red}=0.1 bar ga; $P_{stat}=p_V-1$=0.1 bar ga we can get that NFPA 68 lead to value nearby χ=1.5. It differs in dangerous side from value χ=5, which can be obtained for such conditions by use of formula (3) with $F/V^{2/3}$=0.25 (notice, that given above formula for χ obtained on NFPA 68 base don't contain dependence on F or $F/V^{2/3}$, that is evidently wrong). For "undefined" conditions and respectively large volume we recommend χ=8 for initially covered vents (see Table) and χ=2 for uncovered vents without initial turbulence and turbulence-producing internal appurtenances. It's more than values, corresponding to NFPA 68 recommendations (for V=10000 m^3 from NFPA 68 data we can get only χ=1.9 for considering case).

To prevent catastrophes in industry NFPA 68 "Guide for Venting of Deflagrations" (1988 Edition) must be changed in maximum short time.

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FLAME MERGING FROM TWO RECTANGULAR FIRE SOURCES IN PARALLEL CONFIGURATION

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Abstract

Merging behavior of flames from two rectangular fire sources (2cm x 80cm, and 2cm x 40cm) in parallel configuration was studied theoretically and experimentally. Propane gas, as a fuel, gave 9.5 – 57 kW per unit length. Height of flame merging started, L_m, was estimated based on the vertical and horizontal distributions of temperature and upward velocity. L_m showed linear dependence on the separation, S, between two parallel fire sources and not on the heat release rates. Dimensionless merging height, S/L_m, is expressed as a coupled function of dimensionless heat release rate Q^*_{rec}, Froude Number, and separation factor of (1–W/2S). Merged and/or inclined flame tip heights consist of two flames, L_{fm}, were estimated based on visual data which decreased as separation distance increased with the correction factor of $((S^2+2DW)/2(S^2+DW))^{2/3}$, where D and W are shorter and longer length of a rectangular burner.

Key Words : flame merging, parallel line fire sources, merged flame tip height, entrainment effect

1. Introduction

When an air entrainment into a flame is restrained by other nearby a flame or flames, the flame extends by merging or by interaction with other flame. The multi–fire sources problem including flame merging[1], of which behavior must be complex, occurs in the developing stage in a compartment fire and in a city fire. For a first analysis, a considerably simplified model on a flame merging is necessary. Here only two nearby line (rectangular) fires in paralleled configuration are considered changing the separation distance to study the flame merging behavior.[2] Experiments have been conducted to measure the visible flame tip height. Temperature, upward velocity and CO_2 concentration along the center line between two fire sources. One of the characteristic flame height, L_m, where the flames just start to merge, was estimated based on the vertical and horizontal distributions of temperature, upward velocity, and CO_2 concentration. The merged flame tip height, L_{fm}, consists of two flames, was evaluated by eyes observation and by successive 300 frames of a video recordings. Increase of separation between two fire sources resulted the reduction of merged flame tip height. These experimental results were compared with ones estimated from the theoretical model.

2. Theoretical Procedure

2–1. Merging Height, L_m

A flame and/or hot plume from a line fire source induces an air entrainment from its surroundings. When the other line fire source is placed parallel in the neighborhood, restriction of an air entrainment is caused with result of pressure drop in the space between the two fires. The flames are thus deflected from vertical and merge together.[2] Consider two rectangular fire sources of gas diffusion burners with the long sides being parallel keeping the separation, S, as shown in Figure 1. We assumed the radius of curvature of each flame is large compared with its length up to the marginal location so that the axis of inclined flame was taken as straight. Then the only forces acting on the flames are the buoyancy, B, and a resultant pressure thrust, P, acting normal to the buoyant force. The viscous forces with ambient air and the upward thrust from the burner were neglected because which are generally negligible in actual fire. Let each axis of approaching flames be inclined at angle ϕ to the vertical, then we get $B \cdot \tan\phi = P$. The buoyancy force is due to the density difference between the flame and ambient air and acts on a hot gases of related volume of $D \cdot W \cdot L_m$. As a first approximation, θ_f is assumed constant over the starting of merging height and cross section, W and D, of the flame, giving a buoyancy $B = \rho_f \cdot \theta_f \cdot g \cdot D \cdot W \cdot L_m / T_o$. When the flames merge at height of L_m resulting the approximately triangle cross section of the ends, entrainment air flows is ceased at around the top of the triangle cross section. If u is the average velocity of the entrainment air flowing into the flame, pressure thrusts from outer and inner sides of the flames are estimated by equation (1). Then, the pressure difference causes the inclination of flames is estimated.

$$p_{out} = (1/2) \cdot \rho u^2 \cdot W \cdot L \cdot 2, \qquad p_{in} = (1/2) \cdot \rho u^2 \cdot (1/2) S \cdot L \cdot 2 \qquad (1)$$

We assumed more that entrainment air velocity u is unaffected by the pressure drop on the both ends or by the flames leaning. The pressure thrust, P, on the flames for small value of ϕ is given by $P = p_{out} - p_{in}$. When the flames start to merge, $\tan\phi = (1/2) \cdot S/L_m$. Rearranging with an assumption of entrainment air velocity, u, could be expressed as a ratio of upward velocity, V, we obtain equation (2).

$$\frac{S}{L_m} = \alpha \left[\frac{V}{Q_{rec}^{*\,1/3} (g \cdot D)^{1/2}} \right]^3 \cdot \left(1 - \frac{S}{2W}\right) \qquad (2)$$

where α is coefficient determined by experiments including the ratio between entrainment velocity and upward flame velocity of u/V. The first term of the right side of equation (2) can be rewritten as $Fr^3 \cdot Q_{rec}^*$ having a constant so that the L_m will be given as function of S and W only.

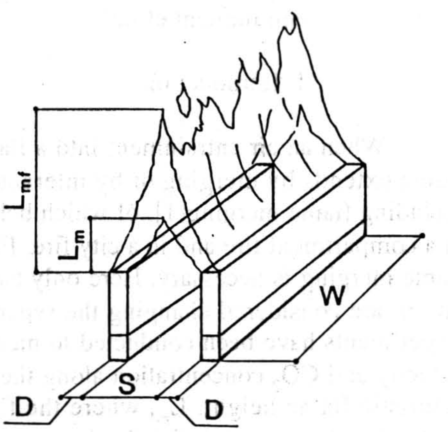

Figure 1 Sketch of the flame merging from two gas diffusion burners and definition of L_m and L_{mf} are also illustrated. S: separation, D: shorter length of the burner, W: longer length of the burner.

2–2. Merged Flame Tip Height, L_{mf}

When two rectangular fire sources are set without separation, they show twice greater heat release rate from burning area of 2DW resulting flame tip extension of $2^{(2/3)}$ times higher [2] than one from an isolated burner. The merged flame tip height, L_{mf}, is a function of Q, D, W, and S. Let the merged flame height without separation, L_o, as the reference height with having reference dimensionless heat release rate, Q_o^*. As the separation increases, dimensionless flame tip height, L_{mf}/L_o, decreases as a function of the apparent burning area and air entrainment. The contribution factor for flame extension is given by $2DW/2(S^2+DW)$, and for flame height reduction by separation increasing is given by $S^2/2(S^2+DW)$, so that the overall correction factor, ϕ, on a merged flame height is; $\phi = (S^2+2DW)/2(S^2+DW)$. Therefore, the dimensionless flame height merged or interacted, L_{mf}/L_o, should be given as;

$$L_{mf}/L_o = (\phi \cdot Q^*_{rec}/Q_o^*)^{2/3}. \quad (3)$$

3. Experimental Procedure

Two series of tests were carried out. The first test was made for measurements of upward velocity, temperature, and CO_2 gas concentration in the space between two burners. The visible flame tip heights were observed and recorded by a video system in the second tests. Both tests were conducted in a calm atmosphere. Diffusion gas burners, 2cm x 40cm and 2cm x 80cm made of stainless steel with fine sand as stuff diffuser, were used. Propane gas was used as a fuel. In the first test, fuel gas was supplied to produce heat release rates of 9.5, 17.1, 28.5, and 57 kW/m, with the separation of 0.05, 0.12, 0.2, and 0.3m. Burners were set on the base floor keeping the burner surface about 30cm high from the base level avoiding the floor effect on the entrainment. Upward velocity and temperature were measured by means of bidirectional tubes and by K–type thermocouples from 5cm above the burner surface to about 2.5m high. These proves were set on a movable rake with a separation pitch of 10cm. Sample gas was sucked from the hot current using a copper tube and was sent to a CO_2 gas meter (a non–disperse infra–red type gas meter) after the filtration and removal of water vapor. All outputs were recorded every 15 seconds.

4. Results and Discussion

4–1. Start of Merging Height

Figure 2 shows the horizontal profiles of upward velocities in the half part of the space between two burners with 0.3 m separation. The mean velocities, processed for 3 min measured data, are shown with their maximum and minimum values. In the lower space, the location of a peak in the horizontal profile of upward velocity approaches toward the center line. As the flames flow up to about 0.7m, in this case, they merge together resulting a merged flame. After the merging occurred, upward velocity along the center line displayed no gradient for vertical direction as Yokoi [3] showed experimentally and theoretically for single line fire. This suggests that the upward velocity obtained along the center line increases until the flames approach to the center line and

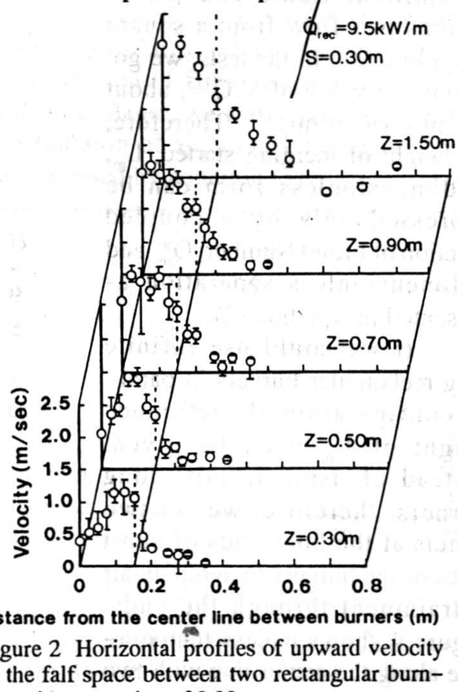

Figure 2 Horizontal profiles of upward velocity in the falf space between two rectangular burners with separation of 0.30 m.

shows no decrease with height after they merged. Figure 3 shows the excess temperatures along the center line with separation of 0.12m. These vertical profiles along the center line indicate that the flow is subdivided into three characteristic regions; pre–approching, approaching, and merged region. No flame exists in the pre–approching space although the induced flow by entrainment give little fluctuation. In the approaching region, flames from two independent fire sources approach toward the center line and their intermittent motion begin to occupy a considerable proportion in the horizontal space between the burners. After two flames meet and merge together, they formed a fire plume in the merged region. In order to make quantitative estimation on the starting height of flame merging, calculations by the least–square methods were carried out for the approaching and merged regions on the two clustered plots of the upward velocities and excess temperatures along the center line. We adopted the crossing point of these two lines as the starting height of the merging, L_m. Figure 5 shows the variation of L_m as a function of dimensionless separation based on the excess temperature profiles along the center line. This figure shows clearly L_m increased with the increase of the separation, S, and not depends on the heat release rates. The increasing behavior of L_m agrees with the expression of equation (2) if we use a fixed burner (constant D and W) and if we have a constant value of $V/Q^{1/3}$. Dimensional analysis and many experimental data given by Yokoi [3], Heskestad [4], and McCaffrey [5] revealed the term of $V/Q^{1/3}$ showed constant in the intermittent flame and plume regions in a flow from a square and a line fire. In the tests, we got a constant value of $V/Q^{1/3}$, about 0.7 m/sec·(kW/m)$^{-1/3}$. Therefore, the height of merging started, L_m, in dimensionless form can be expressed only by a coupled function of Froud Number, Q^*_{rcc} and a dimensionless separation as presented in equation (2).

If we could use infinite long rectangular burners in parallel configuration, the reference height of L_m must be given. Instead of using infinite long burners, therefore, we set two panels at the both ends of short sides of the burners to avoid an air entrainment through the ends. Figure 4 shows excess temperature along the center line with two panels were set at the both ends.

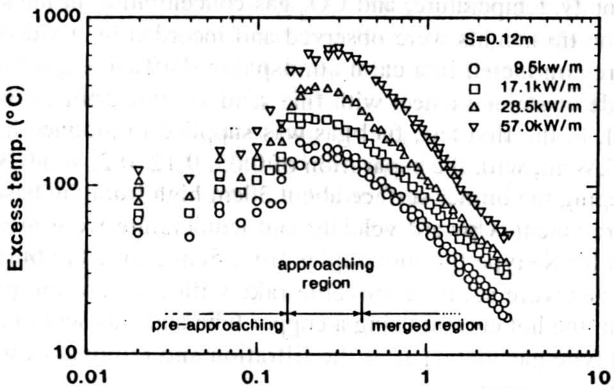

Figure 3 Variations of excess temperature measured along the center line between two burners with separation of 0.12m.

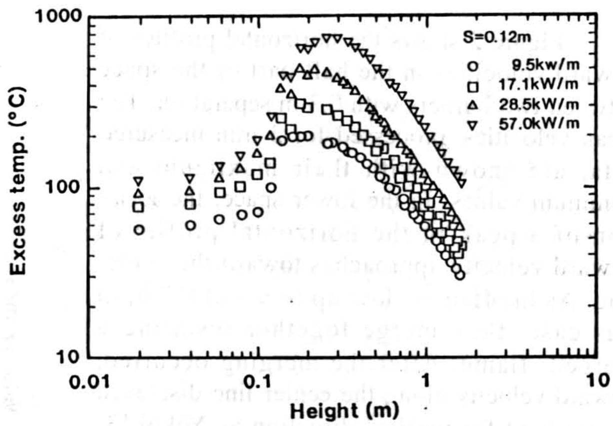

Figure 4 Variations of excess temperature measured along the center line between two burners with separation of 0.12m. Two gypsum panels were set at the both ends to avoid the air entrainment through the triangle cross section consists of flames.

The same method on the estimation of L_m for the test with panels were carried out and give the lowest slope in figure 5. Then, the value $\alpha(V/[Q^{*}_{rec}{}^{1/3}\cdot(gD)^{1/2})])^3$, was estimated from the lowest slope taking S/2W = 0. Substituting the values of $V/Q^{1/3} = 0.7$ and $(gD)^{1/2} = 0.44$ into this term, and then $\alpha = 0.14 \pm 0.01$ is evaluated. Thus, from this value the entrainment velocity, u, can be estimated. In order to validate the expression of equation (2), we carried out the estimations on L_m for the 2cm x 40cm, and 2cm x 80cm burners with various separations using α of 0.14 ± 0.01. For example, setting the separation of 0.2m, L_m of 0.45m – 0.52m and of 0.27m – 0.31m are estimated for those burners, respectively. The obtained values from the excess temperature profiles are about 0.5m and 0.4m, respectively. These calculated values are close to the estimated ones so that the simple model, as expressed in equation (2), is applicable to estimate the starting height of flame merging.

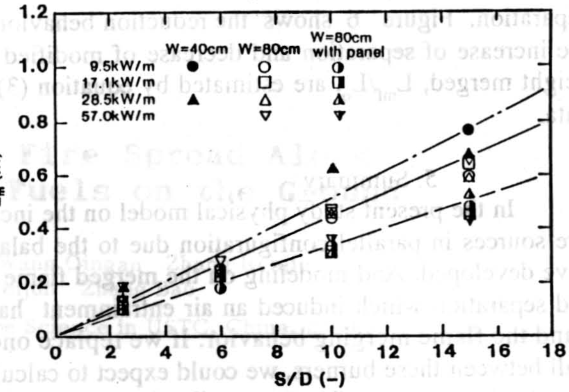

Figure 5 Variation of starting height of the flame merging, L_m, versus dimensionless separation distance. Upper slop was obtained using 40cm burner, middle slope 80 cm, and lower slope with gypsum panels at the both ends.

4-2. Visible Flame Tip Height Merged, L_{mf}, with Separation Change

Measurements were made mainly on visible (not only by eyes but also by a TV camera) flame tip height, changing the separation distance and gas flow rates. After flames showed a quasi-steady state, 3 minutes after ignition in most cases, flame tip height with and without merging were estimated on 300 successive frames of video recordings. [4] The flame tip height was measured from the burner surface. For a general presentation of flame height as a function of heat release rate and mixing factor [4] due to entrainment to flame, we tentatively assume that the balance between entrainmnt and burning area is a function of apparent burning area and separation area. Thus, we assumed these factors can be expressed by equation (3).

The merged flame height without separation, L_o, for each fuel supply rate are estimated independently based on the correlation of $L_o/D = 6.3 \cdot Q^{*}_{rec}{}^{2/3}$ [4] and then dimensionless flame height merged, L_{mf}/L_o, are estimated. These dimensionless flame height merged and are plotted against dimensionless separation, S/D, as shown in Figures 6. If we could set an infite separation between two burners, this means the two independent burners, the flame height reduce to $(1/2)^{2/3}$ or 0.63 of the merged flame height without

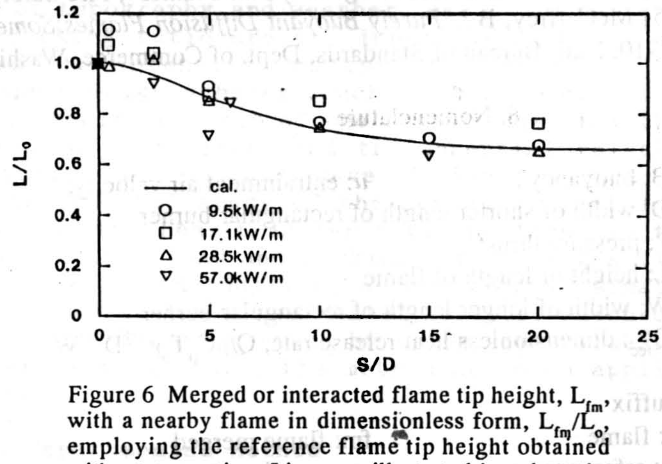

Figure 6 Merged or interacted flame tip height, L_{fm}, with a nearby flame in dimensionless form, L_{fm}/L_o, employing the reference flame tip height obtained without separation. Line was illustrated based on the equation (3).

separation. Figure 6 shows the reduction behavior of flame height merged which is caused by the increase of separation and decrease of modified heat release rate. The dimensionless flame height merged, L_{mf}/L_o, are estimated by equation (3) and are plotted also with the experimental data.

5. Summary

In the present study physical model on the inclination on the flames from two rectangular fire sources in parallel configuration due to the balance between pressure thrust and buoyancy have developed. And modeling on the merged flame tip height considering an apparent fire size and separation which induced an air entrainment have been also developed in order to understand the flame merging behavior. If we replace one burner by an imaginary burner and set a wall between these burners, we could expect to calculate the extended flame height when a rectangular burner approches to a wall using equation (3). With some certain modification but on the same idea of the model, flame merging expression can be applied to the multi square fire cases and to the flame extension behavior beside the wall and at a corner.

6. Acknowledgement

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7. References

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8. Nomenclature

B: buoyancy , *u*: entrainment air velocity,
D: width of shorter length of rectangular burner
P: pressure thrust
L: height or length of flame
W: width of longer length of rectangular burner
Q^*_{rec}: dimensionless heat release rate, $Q/\rho C_p T_o g^{1/2} D^{3/2} W$.

Suffix
f: flame fm: flame merged
o: reference m: merging started