# Adiabatic Cellular Premixed Flames of Methane (Ethane, Propane) + Oxygen + Carbon Dioxide Mixtures

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#### Introduction

Adiabatic stabilization on flat flame burners is attractive for laminar premixed planar and cellular flame studies since it facilitates comparison with theoretical models. Therefore a Heat Flux method was used to determine flame propagation speeds under conditions when the net heat loss of the flame is zero. Experimental measurements of the adiabatic burning velocity for laminar flat flames of  $CH_4 + O_2 + CO_2$  (Konnov et al., 2002) and  $C_2H_6 + O_2 + CO_2$  (Konnov and Dyakov, 2004) were reported recently. Under specific experimental conditions the flames become cellular; this leads to significant modification of the flame propagation speed (Konnov and Dyakov, 2003, 2004). In addition to the propagation speeds of  $C_2H_6 + O_2 + CO_2$  published recently (Konnov and Dyakov, 2004), visual and photographic observations of these flames are reported in the present work. Measurements in  $CH_4 + O_2 + CO_2$  mixtures were repeated on a perforated plate burner of improved design. New measurements are compared with recent results from this group (Konnov and Dyakov, 2003). Finally, adiabatic propagation speeds of premixed cellular flames of  $C_3H_8 + O_2 + CO_2$  and quantification of their cellular structure are presented.

#### **Experimental Details**

The experimental set-up for stabilizing an adiabatic flame using the Heat Flux method has been described elsewhere (Dyakov et al., 2001, Konnov and Dyakov, 2004); however, the most relevant details are repeated in the full manuscript and perforated plate burner of improved design is presented. The burner consisted of the burner head mounted on a plenum chamber. The 2 mm thick burner plate perforated with small holes was attached to the burner outlet. The diameter of the burner mouth was 30 mm. The burner head had a heating jacked supplied with thermostated water to keep the temperature of the burner plate constant. In the present experiments this temperature was varied from 313 to 353 K.

#### **Results and Discussion**

It was observed (Konnov and Dyakov, 2003, 2004) that temperature of the burner plate and mixture composition defined the appearance of a flame. Table 1 summarizes experimental conditions at which cellular flames of methane, ethane and propane have been stabilized. Also shown are relevant studies in flames with nitrogen as inert diluent. In the mixtures of methane (Dyakov et al., 2001), ethane (Konnov et al., 2003) or propane with air no cellularity was observed independent of the burner plate's temperature. For instance, measurements of the burning velocity in mixtures of methane + oxygen + nitrogen (Dyakov et al., 2001) were performed with the temperature of the burner plate of 353 K. However, at this temperature lean flames of  $CH_4 + O_2 + CO_2$  were unstable with a clear cellular instability. Increasing the

temperature of the burner plate eliminated this instability. Lowering the temperature of the burner plate extended the range of equivalence ratios over which the cellularity was observed (Konnov and Dyakov, 2003). When this temperature was fixed at 368 K, the flame stabilized closer to its surface, making the flame perfectly flat (Konnov et al., 2002). Then the adiabatic burning velocity in laminar flat flames could be determined.

10001. Conditions at which conduct findes of C114, C/116 and C3118 have been observed	Table 1.	Conditions	at which	cellular fl	lames of	$CH_4$ , $CH_4$	$C_2H_6$ and	$C_3H_8$ ]	have l	been	observ	ved.
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Fuel	Oxidizer	Dilution	Burner plate's	Appea-	Reference
		ratio, %	temperature, K	rance	
CH <sub>4</sub>	$O_2 + N_2$	21	353	Flat	Dyakov et al., 2001
$CH_4$	$O_2 + CO_2$	26 - 35	368	Flat	Konnov et al., 2002
$CH_4$	$O_2 + CO_2$	31.55, 35	323, 338	Cellular	Konnov & Dyakov, 2003
$CH_4$	$O_2 + CO_2$	35	318 - 338	Cellular	This work
$C_2H_6$	$O_2 + N_2$	21	353	Flat	Konnov et al., 2003
$C_2H_6$	$O_2 + CO_2$	26, 29	368	Flat	Konnov & Dyakov, 2004
$C_2H_6$	$O_2 + CO_2$	31.55, 35	338, 353	Cellular	Konnov, Dyakov, 2004, this work
$C_3H_8$	$O_2 + N_2$	21	353	Flat	Unpublished
$C_3H_8$	$O_2 + CO_2$	35	313 - 338	Cellular	This work

Figure 1 shows direct photographs of the cellular lean, stoichiometric and rich  $CH_4 + O_2 + CO_2$  flames. In lean mixtures with an equivalence ratio 0.6 - 0.8, the flame broke down to form a number of individual cells. These cells had the shape of a hemisphere convex towards the fresh mixture and were separated by non-luminous relatively wide zones. When the mixture composition was changed toward the stoichiometric one, the cells joined to form a continuous corrugated flame front. In rich mixtures, the cells were very shallow, the boundaries were not clear and perimeter of some cells was even not complete.



**Figure 1**. Direct photograph of the cellular  $CH_4 + O_2 + CO_2$  flames with dilution ratio D = 35 % and the burner plate temperature of 323K. (a) - equivalence ratio = 0.7; (b) - equivalence ratio = 1.0; (c) - equivalence ratio = 1.2.

Photographic records of  $C_2H_6 + O_2 + CO_2$ , and  $C_3H_8 + O_2 + CO_2$  flames are also presented in the full manuscript. The variation of the appearance of ethane and propane flames with equivalence ratio inversely mirrored that of methane flames. This is not surprising, since the diffusion coefficients of ethane and propane on one hand and of methane on another hand are respectively lower and higher than that of oxygen.

New experimental measurements of the propagation speed of adiabatic cellular flames of  $CH_4 + O_2 + CO_2$  and  $C_3H_8 + O_2 + CO_2$  are presented. Decreasing the temperature of the burner plate led to increase of the propagation speeds. To observe a transition between cellular and flat flames, similar to that found by Botha and Spalding (1954) the velocity of the fresh gas mixture was gradually reduced until the moment when the flame was flattened out.

Konnov and Dyakov (2003) found that there is no direct proportionality between the number of cells observed and propagation speeds in  $CH_4 + O_2 + CO_2$  flames. The local minimum in the number of cells was observed in the stoichiometric mixtures with dilution ratio D = 35 % and the burner plate temperature of 338 K. To quantify the cellular structure of methane flames and to verify this unexpected phenomenon, visual and photographic observations of the flames were performed on the burner of improved design. The number of the cells observed in  $C_2H_6 + O_2 + CO_2$  and  $C_3H_8 + O_2 + CO_2$  flames is presented in the full manuscript. Figure 2 shows the number of cells observed in  $CH_4 + O_2 + CO_2$  flames. It is interesting to note that the burner plate's temperature has very little effect on the number of cells in rich mixtures. In lean and stoichiometric mixtures the variation of the number of cells observed was significant and far above the uncertainty of the count. The existence of the local minimum in the number of cells in the stoichiometric mixtures was undoubtedly confirmed.



**Figure 2**. Number of cells observed in  $CH_4 + O_2 + CO_2$  flames with dilution ratio D = 35 %. Crosses: the burner plate temperature = 318 K; diamonds: the burner plate temperature = 323 K; squares: the burner plate temperature = 328 K; circles: the burner plate temperature = 338 K.

#### Conclusions

New measurements in adiabatic cellular flames of  $CH_4 + O_2 + CO_2$ ,  $C_2H_6 + O_2 + CO_2$ , and  $C_3H_8 + O_2 + CO_2$  are presented. A Heat Flux method was used to determine propagation speeds under conditions when the net heat loss of the flame is zero. Visual and photographic observations of the flames were performed to quantify their cellular structure. These results together with the earlier experiments (Konnov and Dyakov, 2003, 2004) could be summarized as following:

1. Under specific experimental conditions the flames become cellular; this led to significant modification of the flame propagation speed. Increasing the temperature of the burner plate eliminated this instability. Lowering the temperature of the burner plate extended the range of equivalence ratios over which the cellularity was observed.

2. Adiabatic propagation speeds of cellular flames were systematically higher than those in laminar flat flames; the difference was more pronounced at lower temperatures of stabilization. Decreasing the temperature of the burner plate led to increase of the propagation speeds.

3. The onset of cellularity was observed throughout the stoichiometric range of the mixtures studied. Cellularity disappeared when the flames became only slightly sub-adiabatic. The perforated plate flame holder therefore served as a flat flame stabilizer when the flame approached it due to a reduction of the velocity of the fresh mixture or due to an increase of the burner plate's temperature.

4. It was noted that the appearance of the cells varies with equivalence ratio, dilution by  $CO_2$  and the temperature of the burner plate. Increasing the oxygen content in the oxidizer air and increasing the temperature of the burner plate led to increase of the number of cells observed.

5. No direct proportionality between the number of cells and propagation speeds in  $CH_4 + O_2 + CO_2$  flames was observed. Dependence of the number of cells as a function of equivalence ratio clearly showed a local minimum in the stoichiometric mixtures.

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